

# CLIMATE FORENSICS

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**HS-ESS2-4.** Use a model to describe how variations in the flow of energy into and out of Earth's systems result in changes in climate. *[Clarification Statement: Examples of the causes of climate change differ by timescale, over 1-10 years: large volcanic eruption, ocean circulation; 10-100s of years: changes in human activity, ocean circulation, solar output; 10-100s of thousands of years: changes to Earth's orbit and the orientation of its axis; and 10-100s of millions of years: long-term changes in atmospheric composition.] [Assessment Boundary: Assessment of the results of changes in climate is limited to changes in surface temperatures, precipitation patterns, glacial ice volumes, sea levels, and biosphere distribution.]*

**HS-ESS3-5** Analyze geoscience data and the results from global climate models to make an evidence-based forecast of the current rate of global or regional climate change and associated future impacts to Earth systems. *[Clarification Statement: Examples of evidence, for both data and climate model outputs, are for climate changes (such as precipitation and temperature) and their associated impacts (such as on sea level, glacial ice volumes, or atmosphere and ocean composition).] [Assessment Boundary: Assessment is limited to one example of a climate change and its associated impacts.]*

**HS-ESS3-6** Use a computational representation to illustrate the relationships among Earth systems and how those relationships are being modified due to human activity. *[Clarification Statement: Examples of Earth systems to be considered are the hydrosphere, atmosphere, cryosphere, geosphere, and/or biosphere. An example of the far-reaching impacts from a human activity is how an increase in atmospheric carbon dioxide results in an increase in photosynthetic biomass on land and an increase in ocean acidification, with resulting impacts on sea organism health and marine populations.] [Assessment Boundary: Assessment does not include running computational representations but is limited to using the published results of scientific computational models.]*

# An atmospheric whodunit

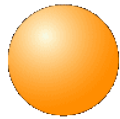
oxygen



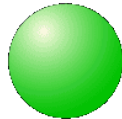
hydrogen



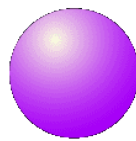
carbon



nitrogen



chlorine

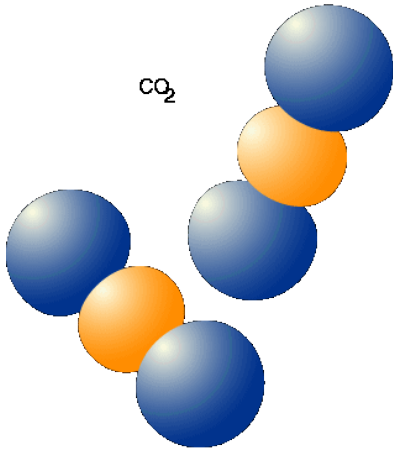


fluoride

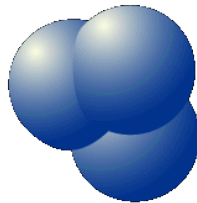


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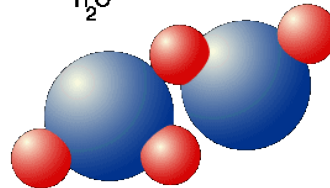
CO<sub>2</sub>



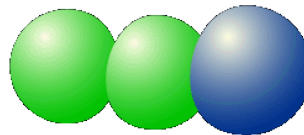
O<sub>3</sub> ozone



H<sub>2</sub>O

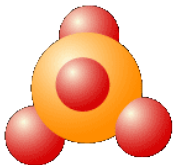


N<sub>2</sub>O nitrous oxide



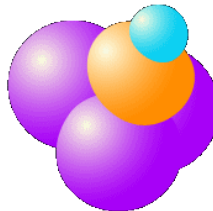
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CH<sub>4</sub> methane



??

CFC chloroflouro carbon

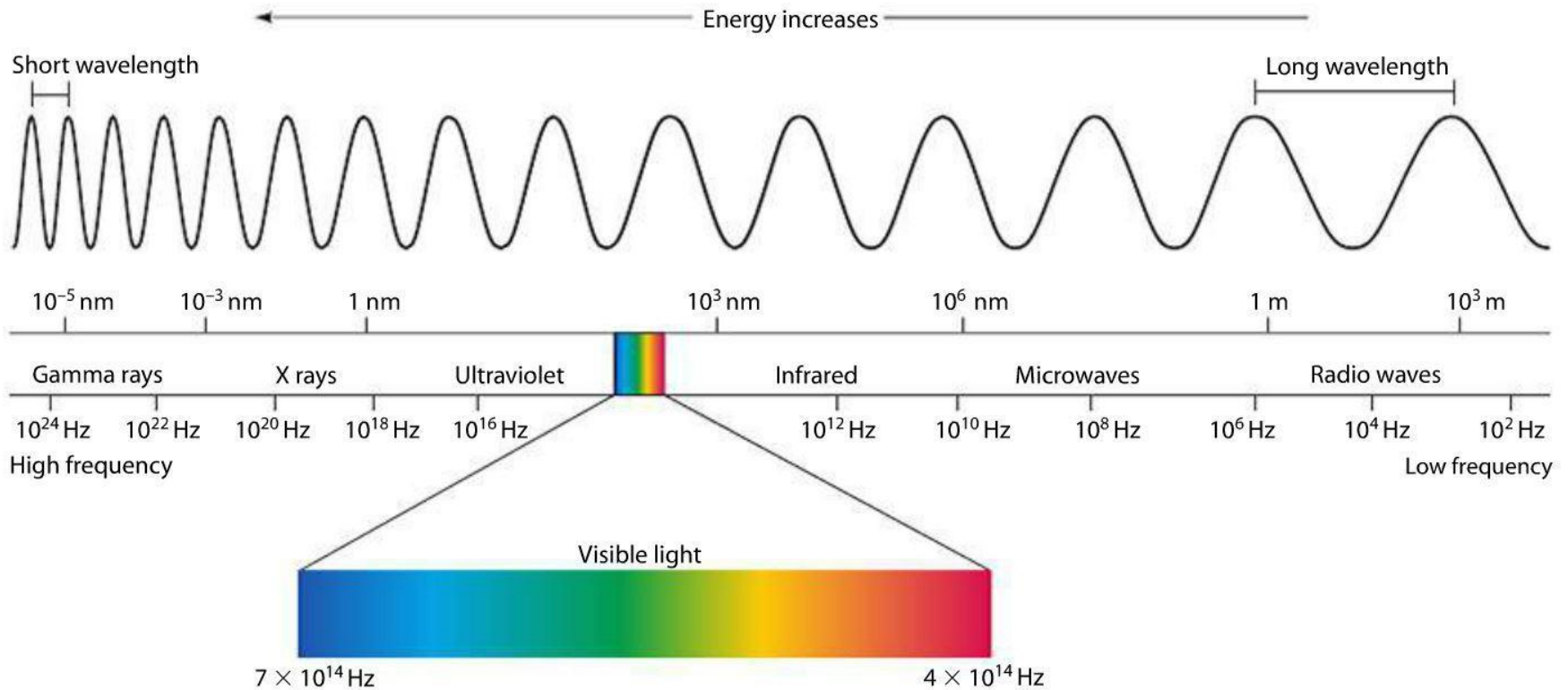


'It is a capital mistake to theorize before one has data. Insensibly one begins to twist facts to suit theories, instead of theories to suit facts.'

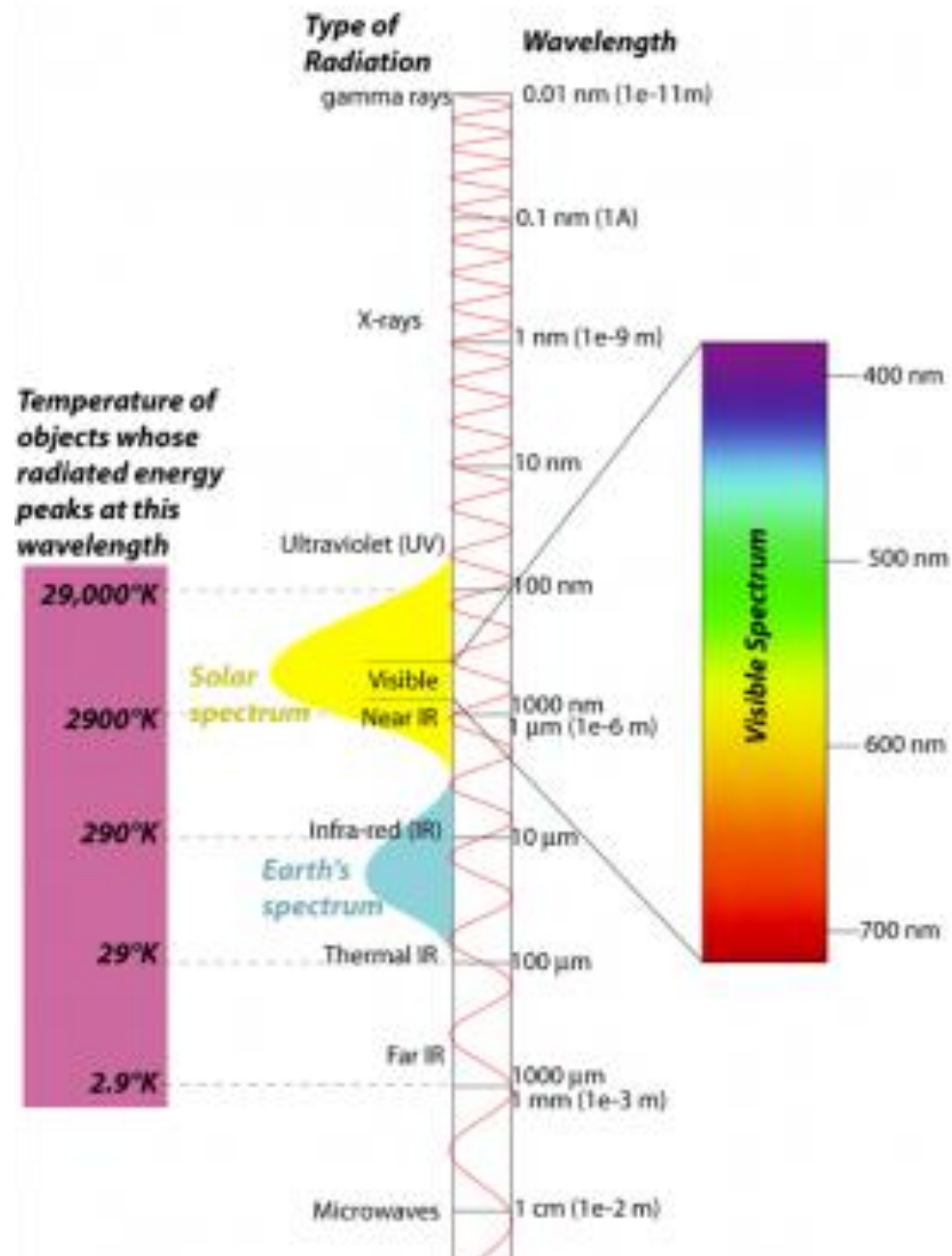
Sherlock Holmes

-*A Scandal in Bohemia*

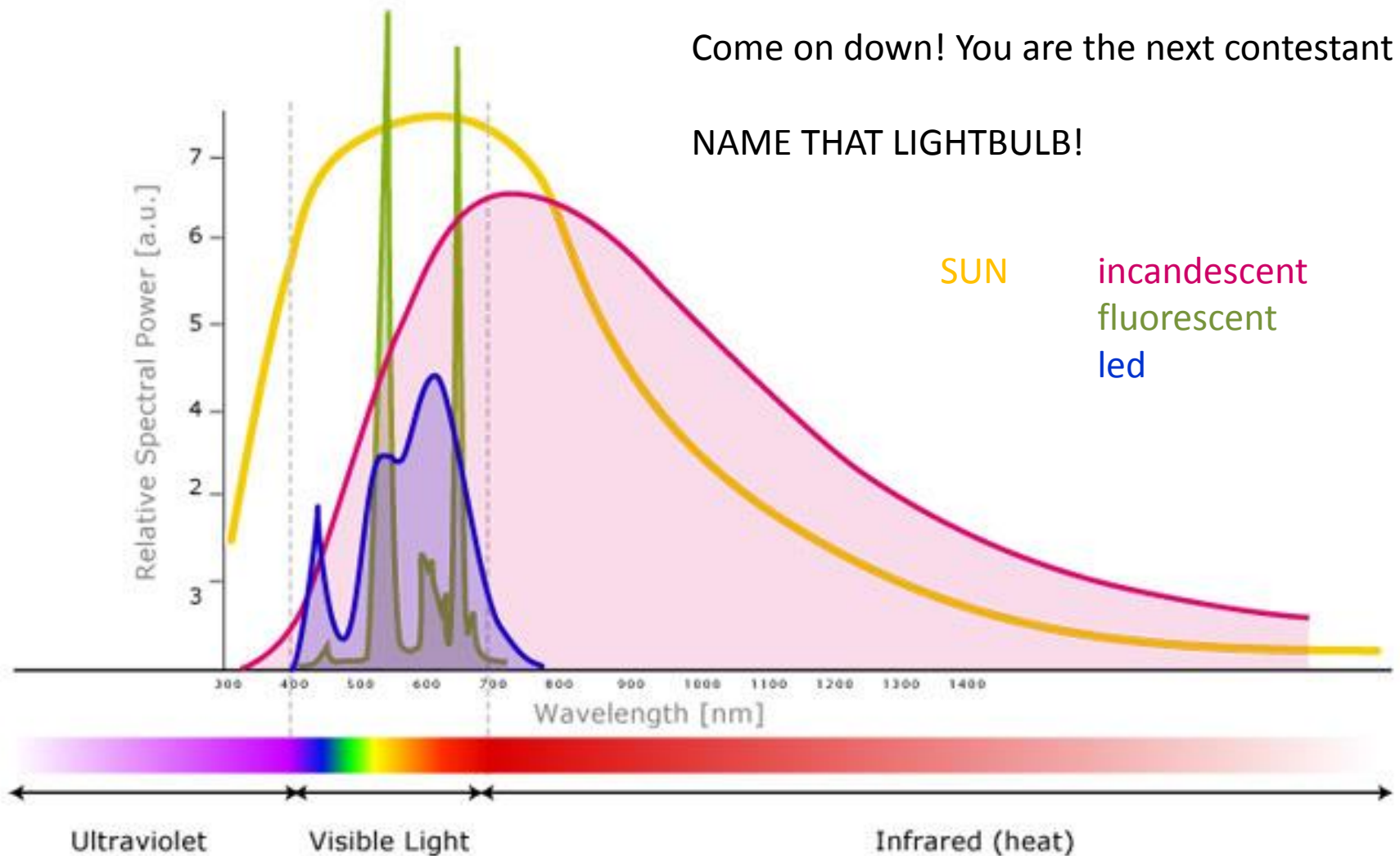
WATSON, LOOK UP  
AT THE SKY AND  
TELL ME WHAT YOU  
SEE.



# The Electromagnetic Spectrum



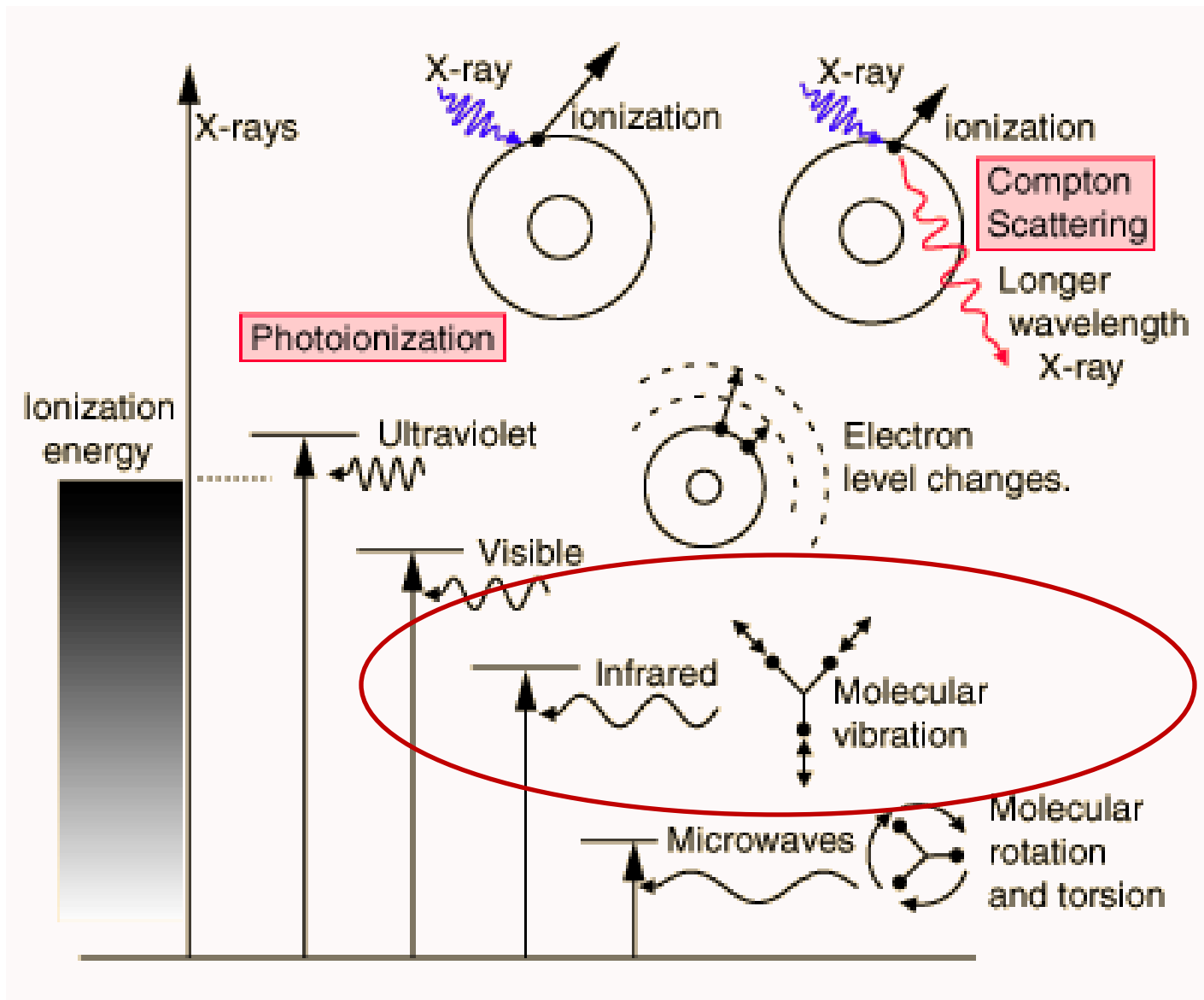
Come on down! You are the next contestant on  
NAME THAT LIGHTBULB!



Except Integrated Sustainability - [www.except.nl](http://www.except.nl) CC-BY-NC-SA

We hear that fluorescents were more efficient than incandescents, and that leds are more efficient than fluorescents. But do we know why?

# The interaction of radiation with matter

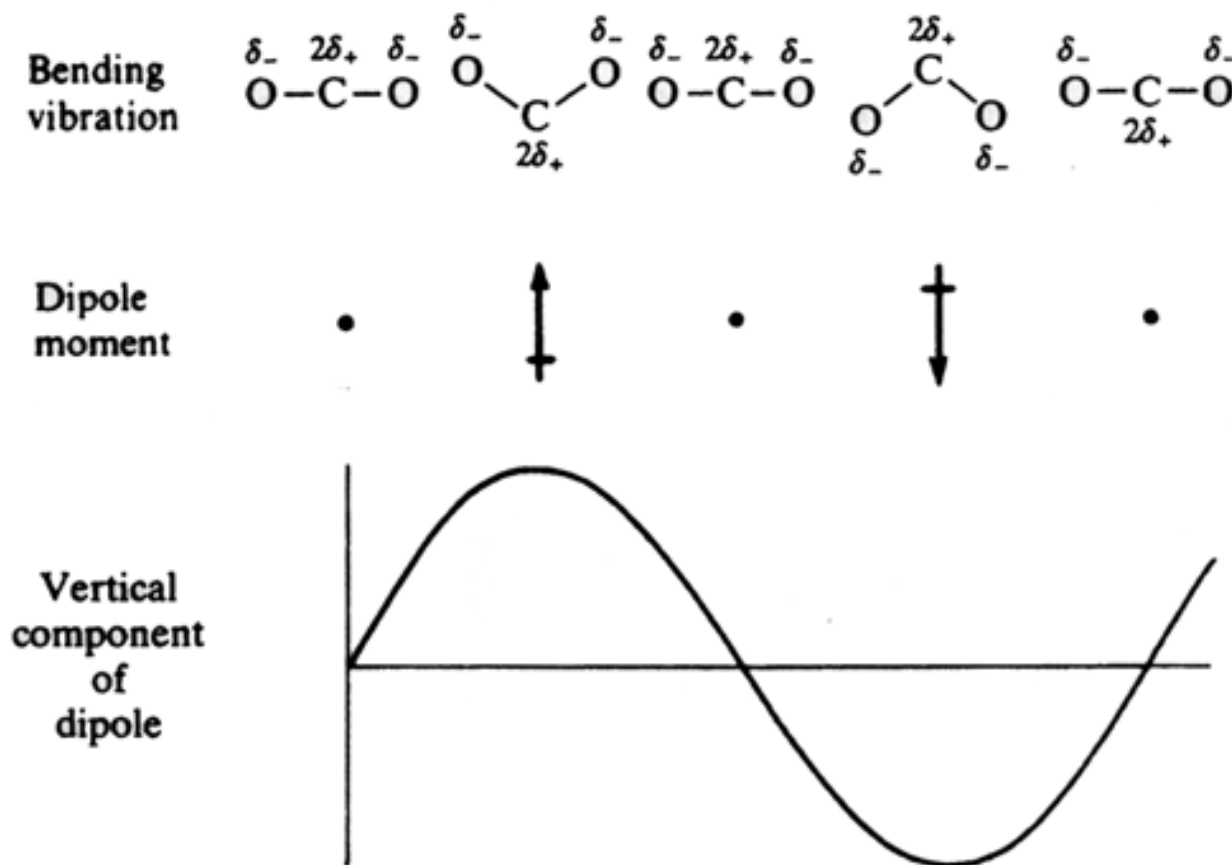


# To absorb in the IR part of the spectrum a molecule must be able to vibrate by stretching or bending

**Types of Molecular Vibrations:** Vibrations fall into the basic categories of stretching and bending.

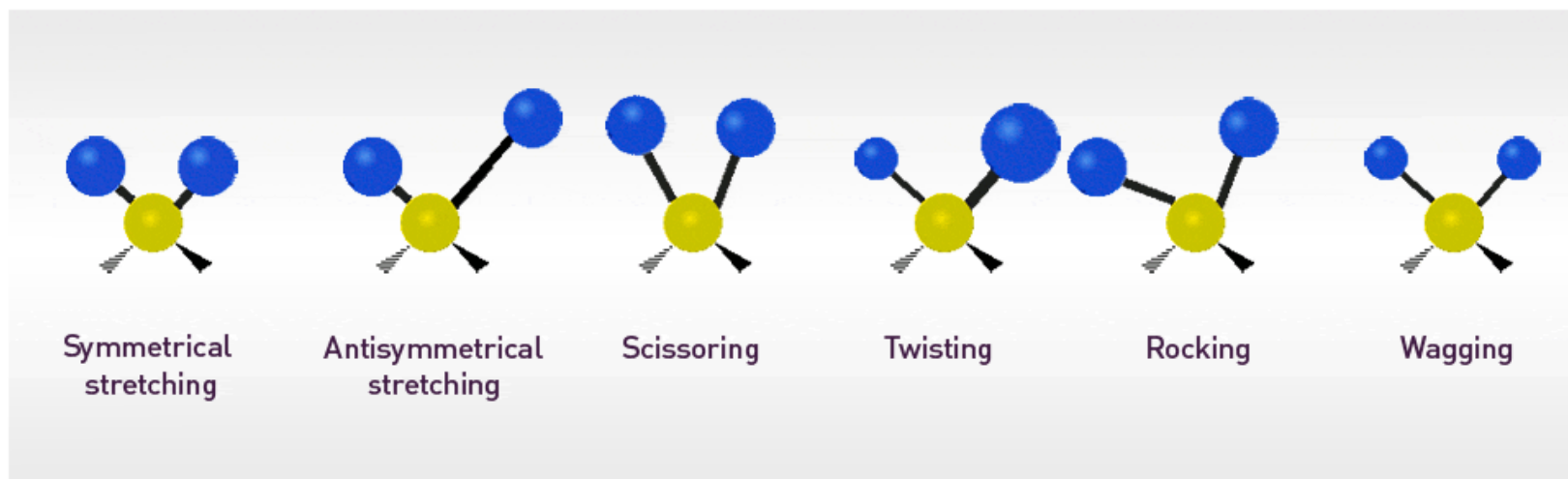
- ❑ **Stretching** vibration involves a continuous change in the inter-atomic distance along the axis of the bond between two atoms.
- ❑ **Bending** vibrations are characterized by a change in the angle between two bonds and are of four types: **scissoring, rocking, wagging, and twisting**.

## Bending motion of the CO<sub>2</sub>



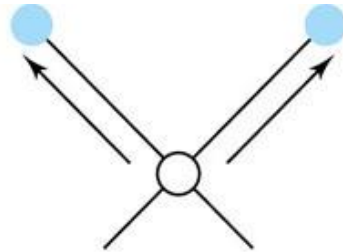
The bending motion of the carbon dioxide molecule and its associated dipole fluctuation.



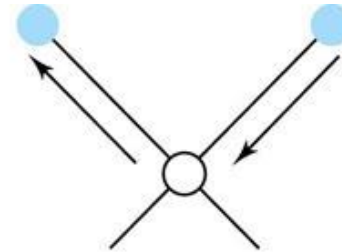


[http://chemwiki.ucdavis.edu/Physical\\_Chemistry/Spectroscopy/Vibrational Spectroscopy/Vibrational Modes/Number of vibrational modes for a molecule](http://chemwiki.ucdavis.edu/Physical_Chemistry/Spectroscopy/Vibrational_Spectroscopy/Vibrational_Modes/Number_of_vibrational_modes_for_a_molecule)

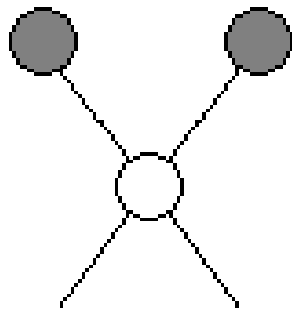
# Stretching Vibration



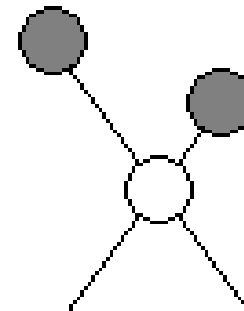
Symmetric



Asymmetric

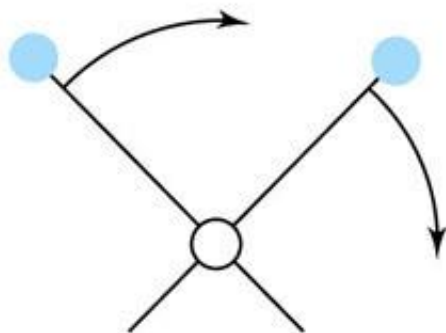


Symmetric

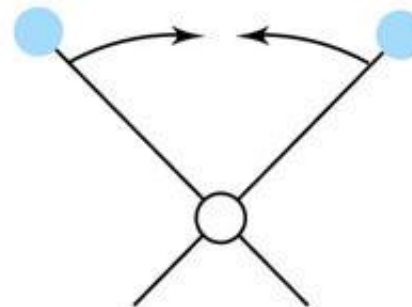


Asymmetric

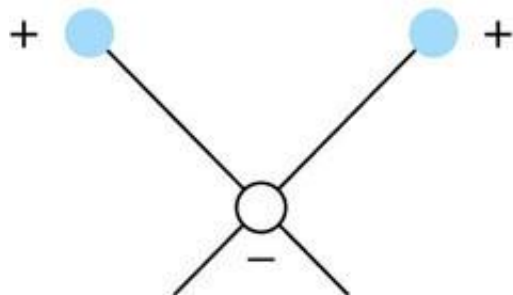
# Bending Vibration



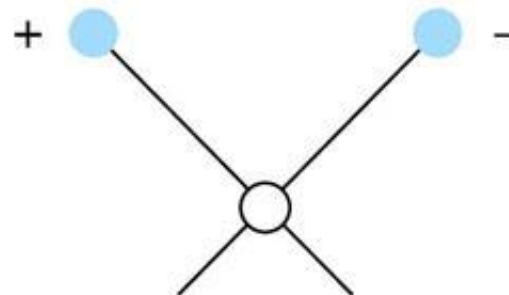
In-plane rocking



In-plane scissoring



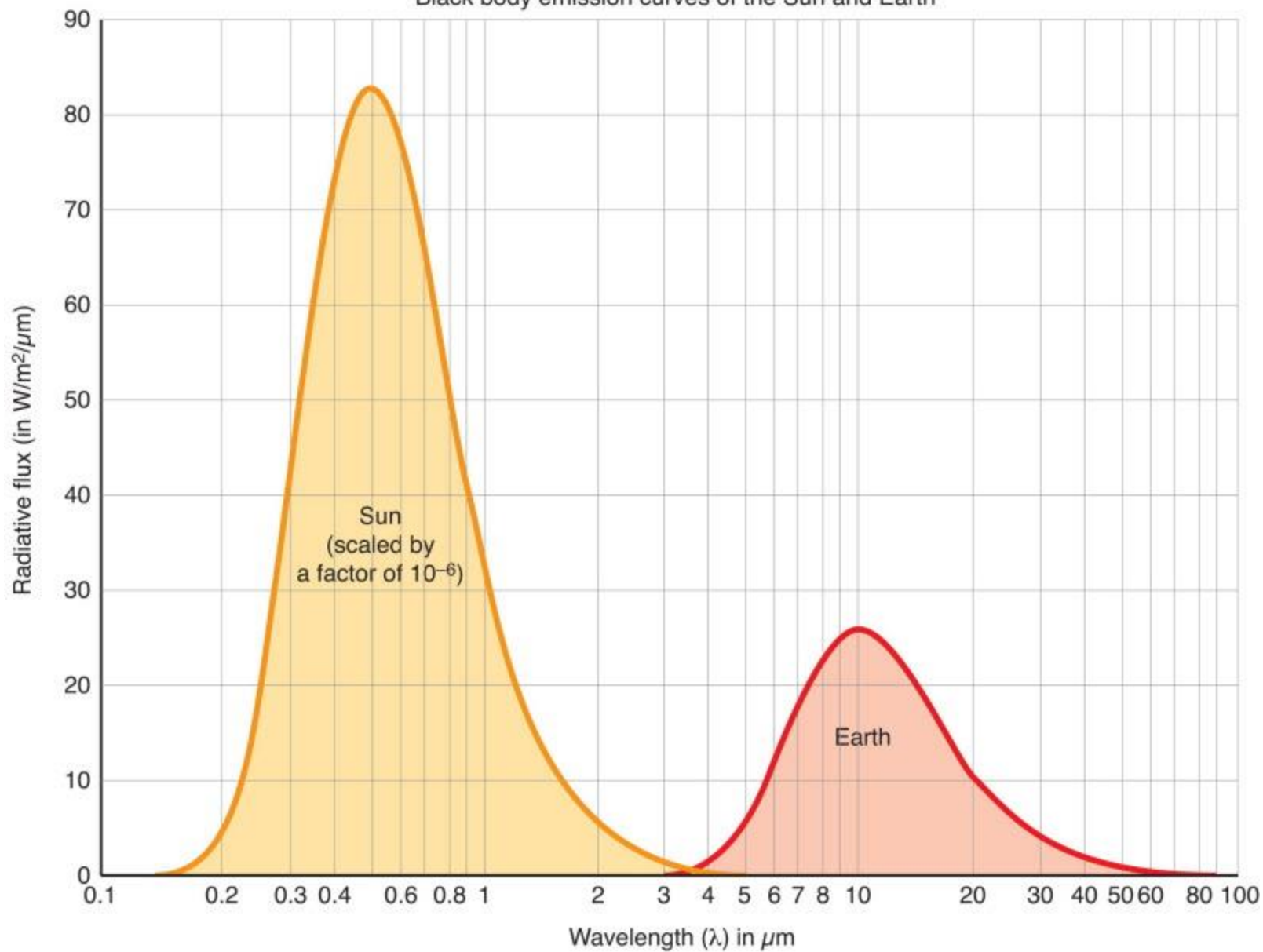
Out-of-plane wagging



Out-of-plane twisting

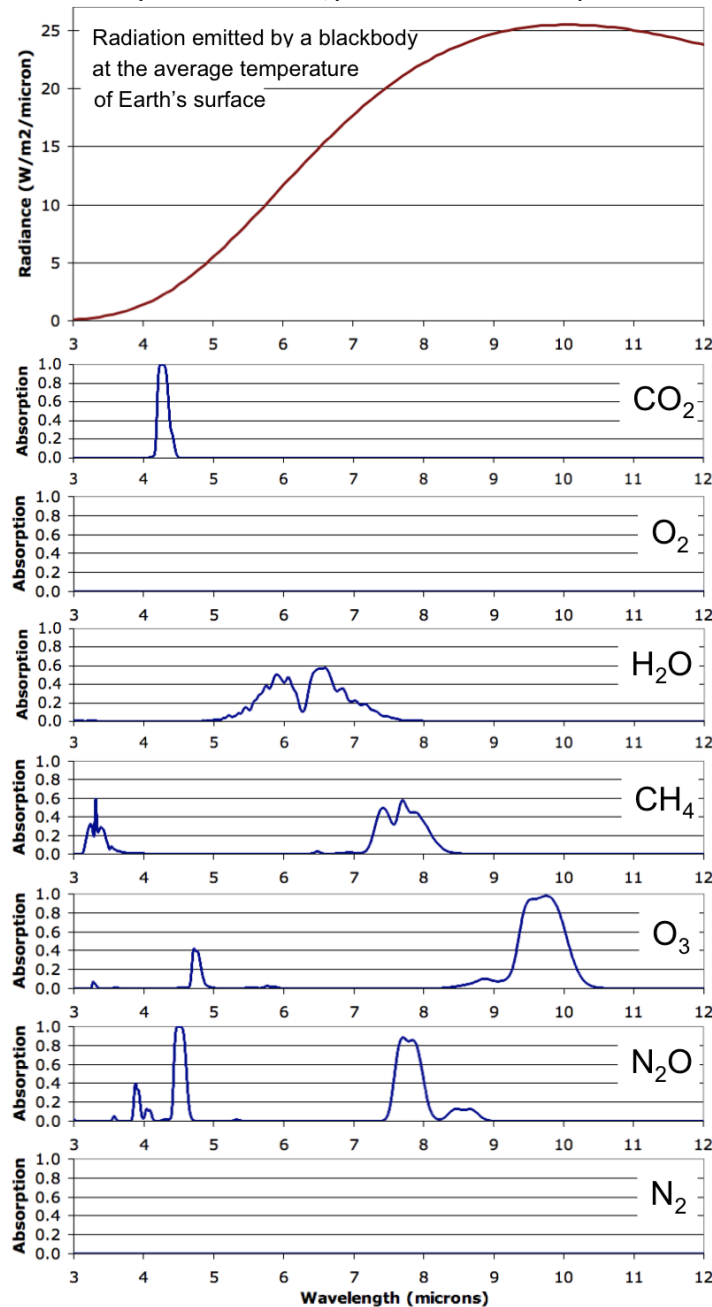
(b) Bending vibrations

Black body emission curves of the Sun and Earth

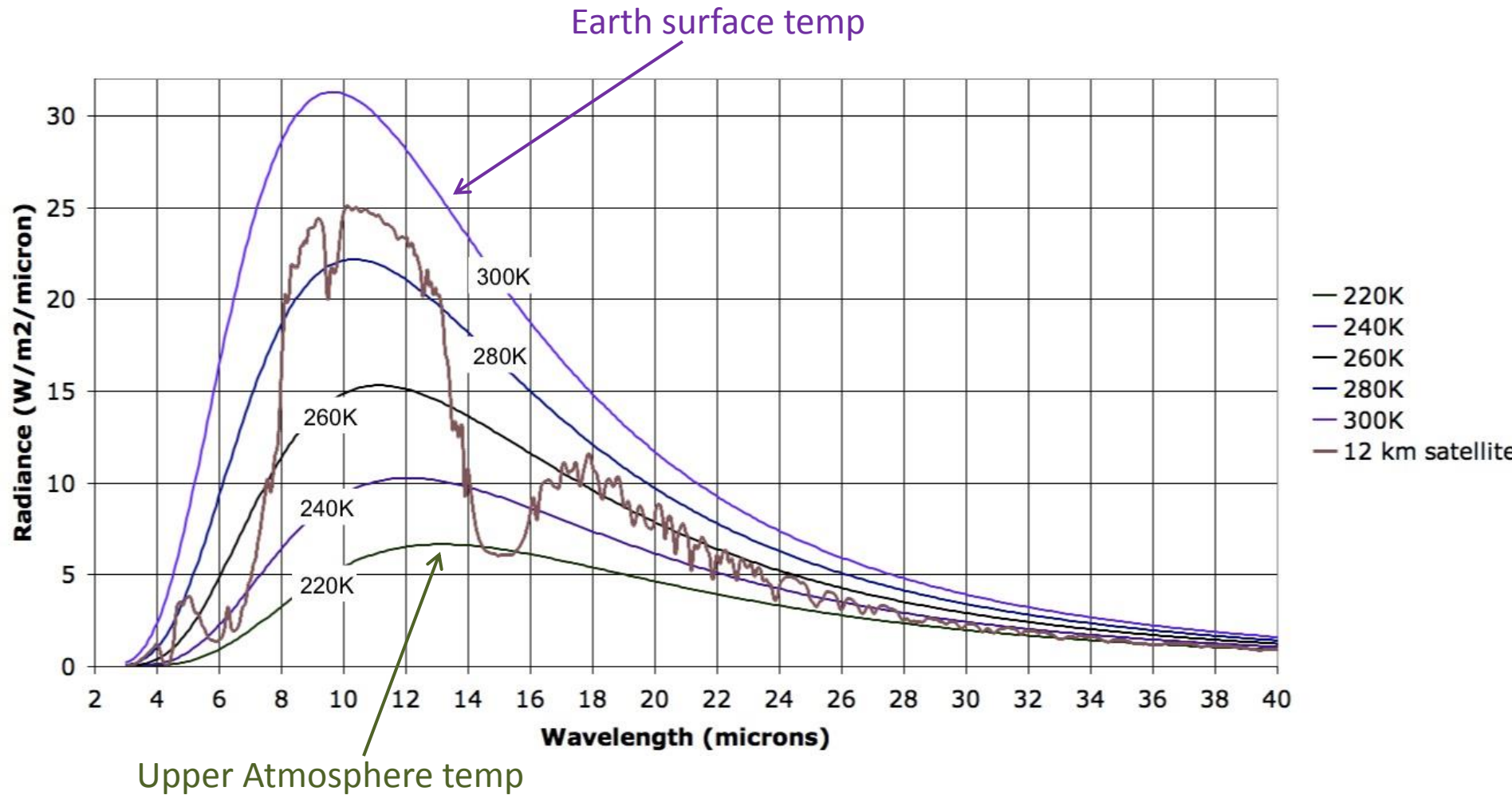


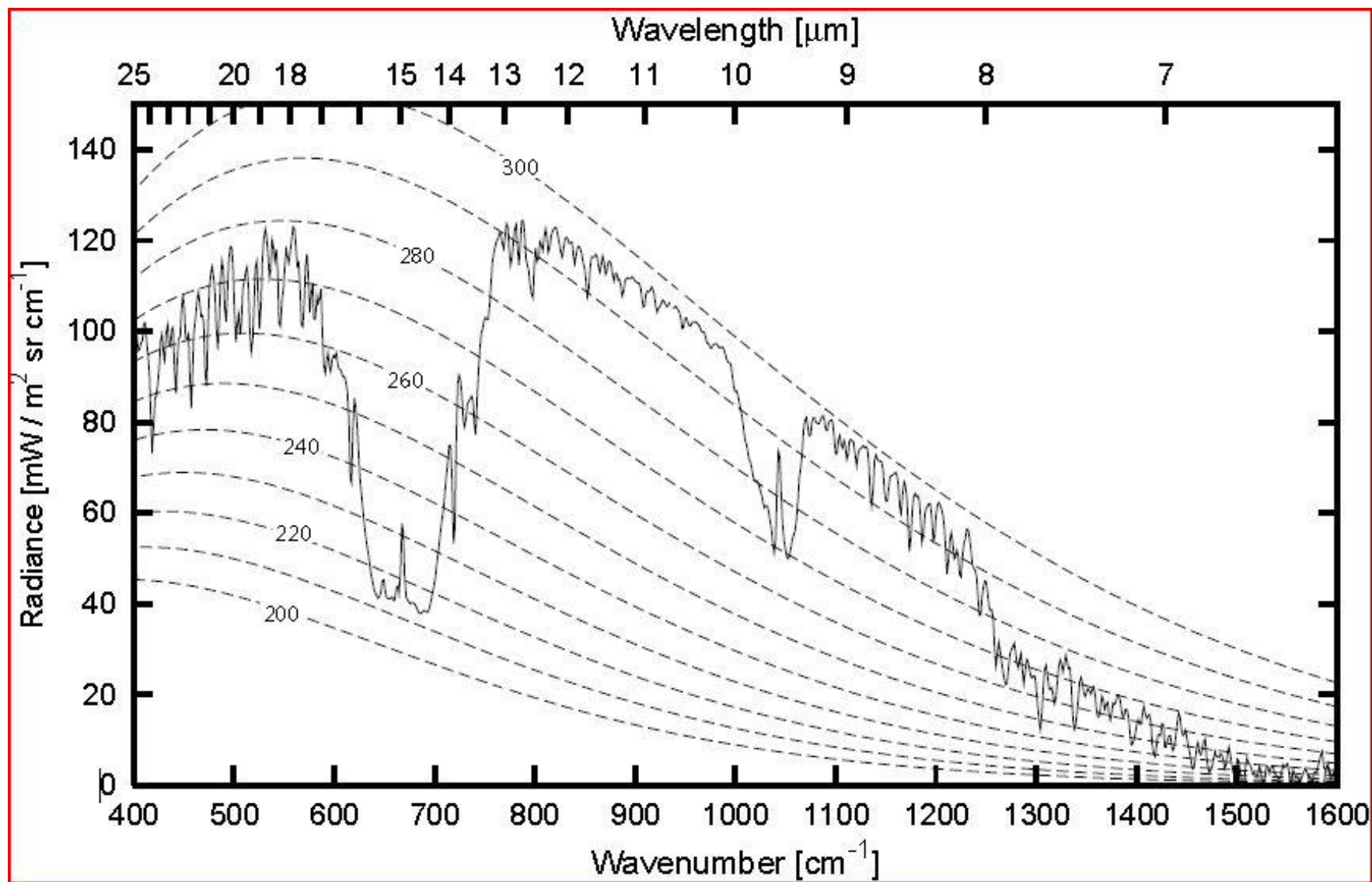
# Absorption by atmospheric gases of incoming and outgoing radiation

adapted from <http://cleanet.org/clean/community/activities/c4.html>



Let's take a look at the actual absorption spectrum and see if we can identify the gas absorption bands





Let's explore the absorption of IR by various gases  
Load the PUFFIN browser app (this allows the ipad to use flash)

## Puffin Browser Free – Fast & Flash

[View More by This Developer](#)

By CloudMosa, Inc.

Open iTunes to buy and download apps.



[View in iTunes](#)

+ This app is designed for both iPhone and iPad

Free

### Description

Puffin Browser is a wicked fast Mobile Flash Browser. Once users experience the thrilling speed of Puffin, regular mobile Internet feels like torture. Puffin Free supports Adobe Flash over cloud 24 hours for Free.

[CloudMosa, Inc. Web Site](#) > [Puffin Browser Free – Fast & Flash Support](#) >

[...More](#)

### What's New in Version 4.4.0

- \* Fix crash on App launch time for some devices.
- \* 24H Unlimited Free Flash service. No more trial time limitation.

### Screenshots

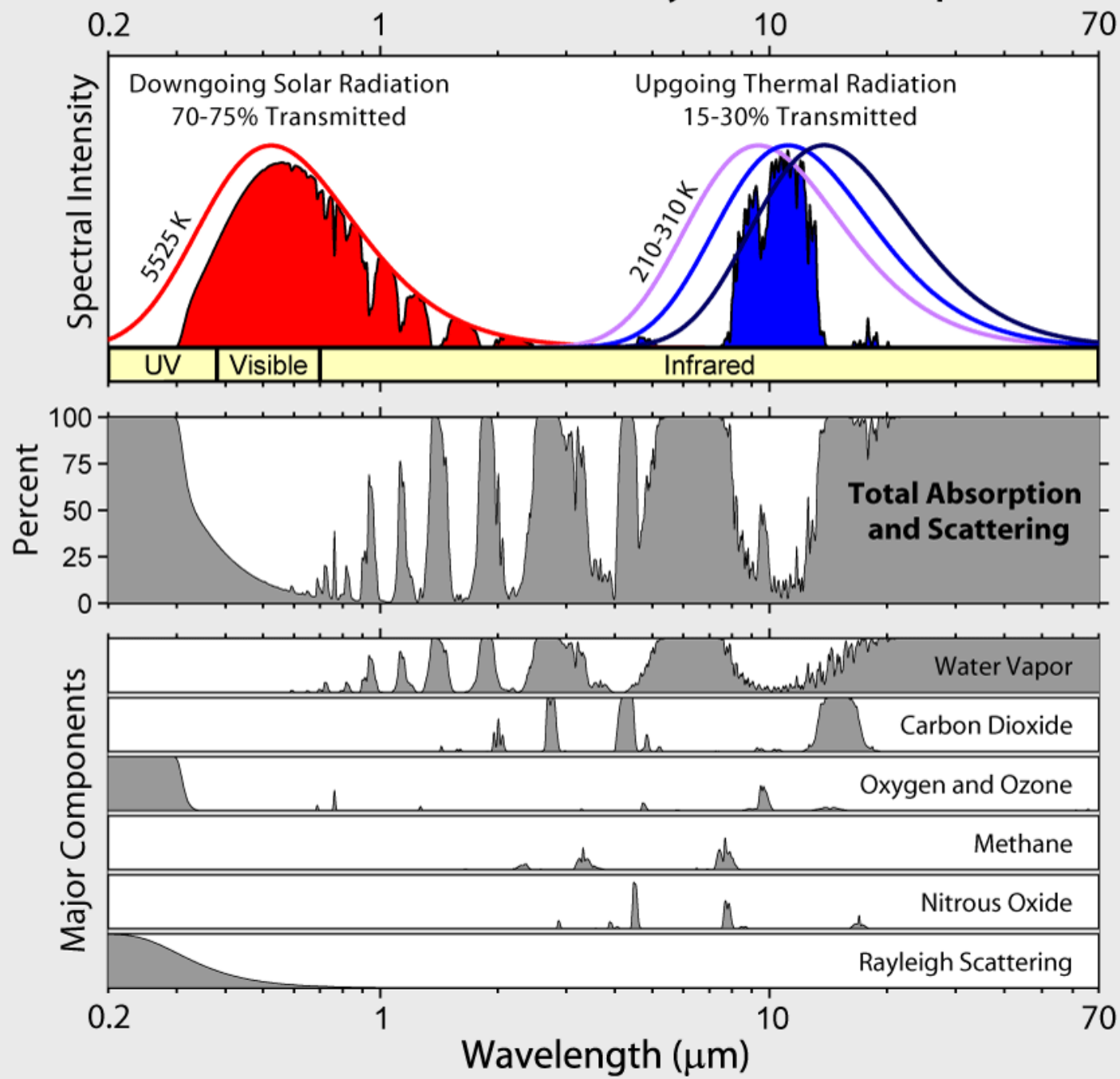
[iPhone](#) | [iPad](#)

Use Puffin to go to this site:

<http://www.chem.arizona.edu/chemt/C21/sim/gh/>



# Radiation Transmitted by the Atmosphere

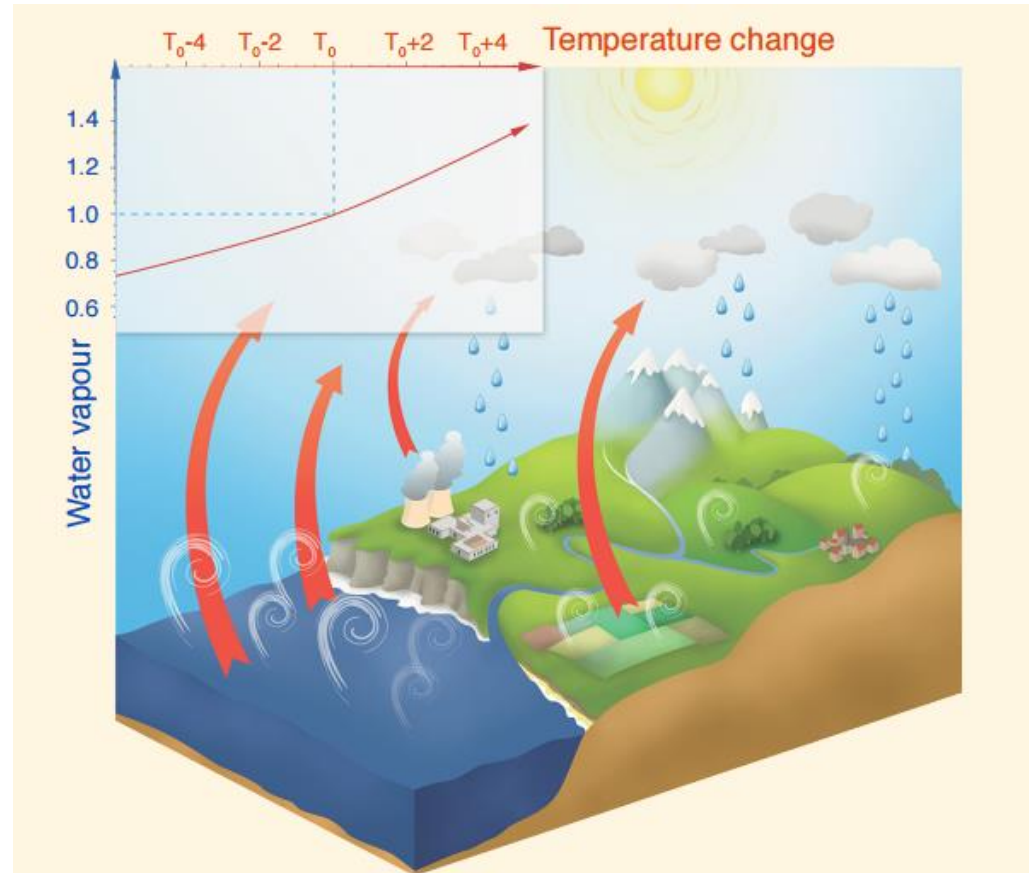


What did we learn from this investigation?

**1 . Water vapor has 2-3x the warming potential as carbon dioxide!**

Because water vapor is controlled by temperature rather than emissions, scientists consider it a feedback agent - it is included in all climate models but is not a target for legislation

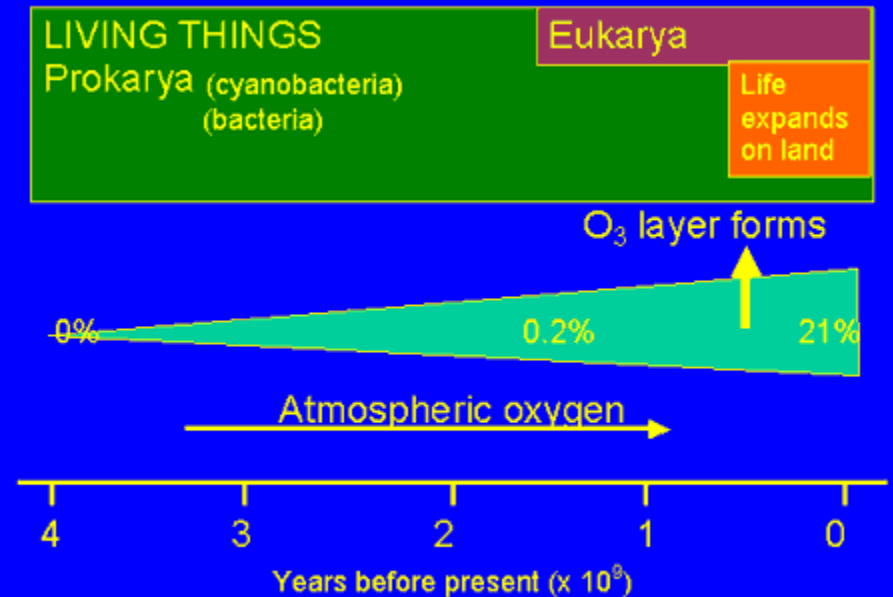
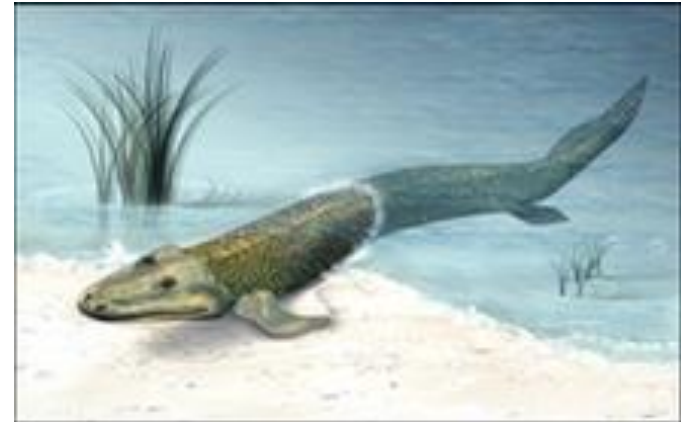
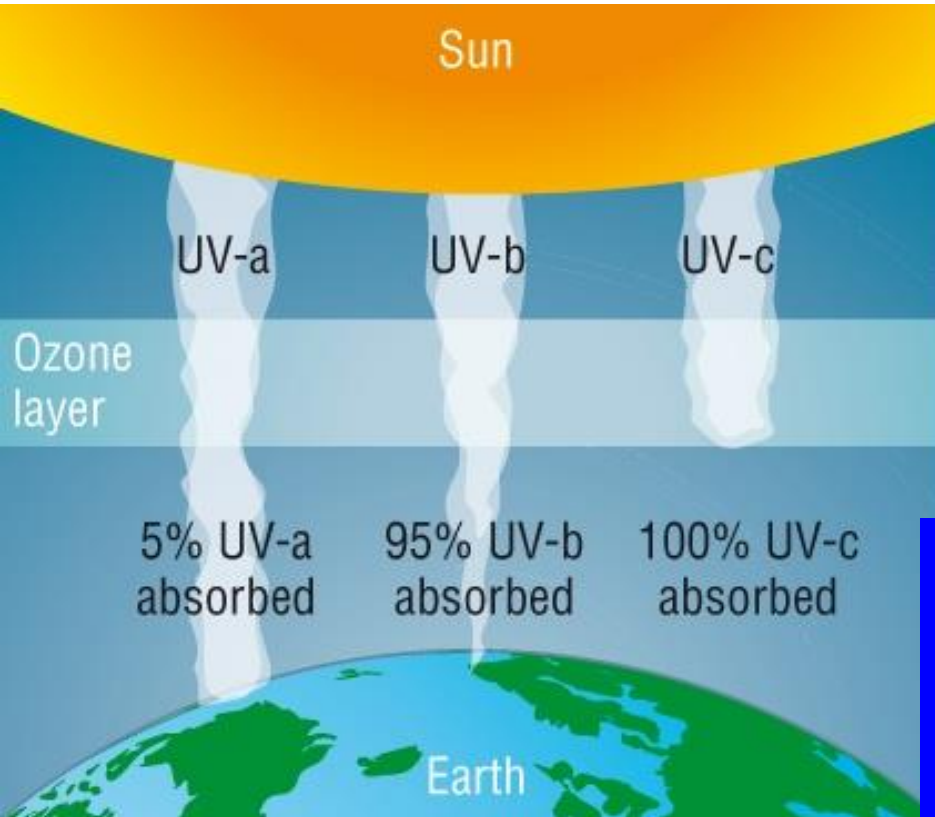
It is also able to condense and evaporate at T&P in the atmosphere and has a very short residence time



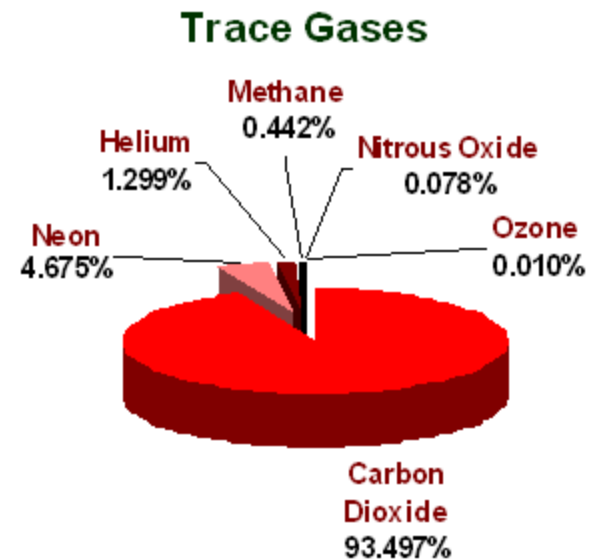
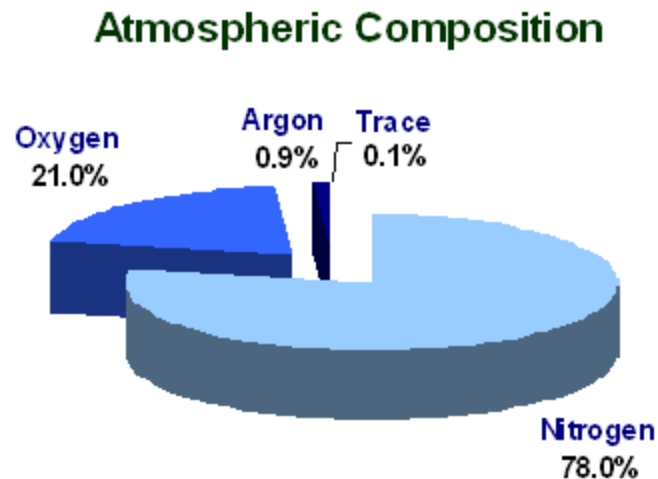
**FAQ 8.1, Figure 1** | Illustration of the water cycle and its interaction with the greenhouse effect. The upper-left insert indicates the relative increase of potential water vapour content in the air with an increase of temperature (roughly 7% per degree). The white curls illustrate evaporation, which is compensated by precipitation to close the water budget. The red arrows illustrate the outgoing infrared radiation that is partly absorbed by water vapour and other gases, a process that is one component of the greenhouse effect. The stratospheric processes are not included in this figure.

## 2. Ozone does a great job of absorbing incoming UV light as well as absorber of IR

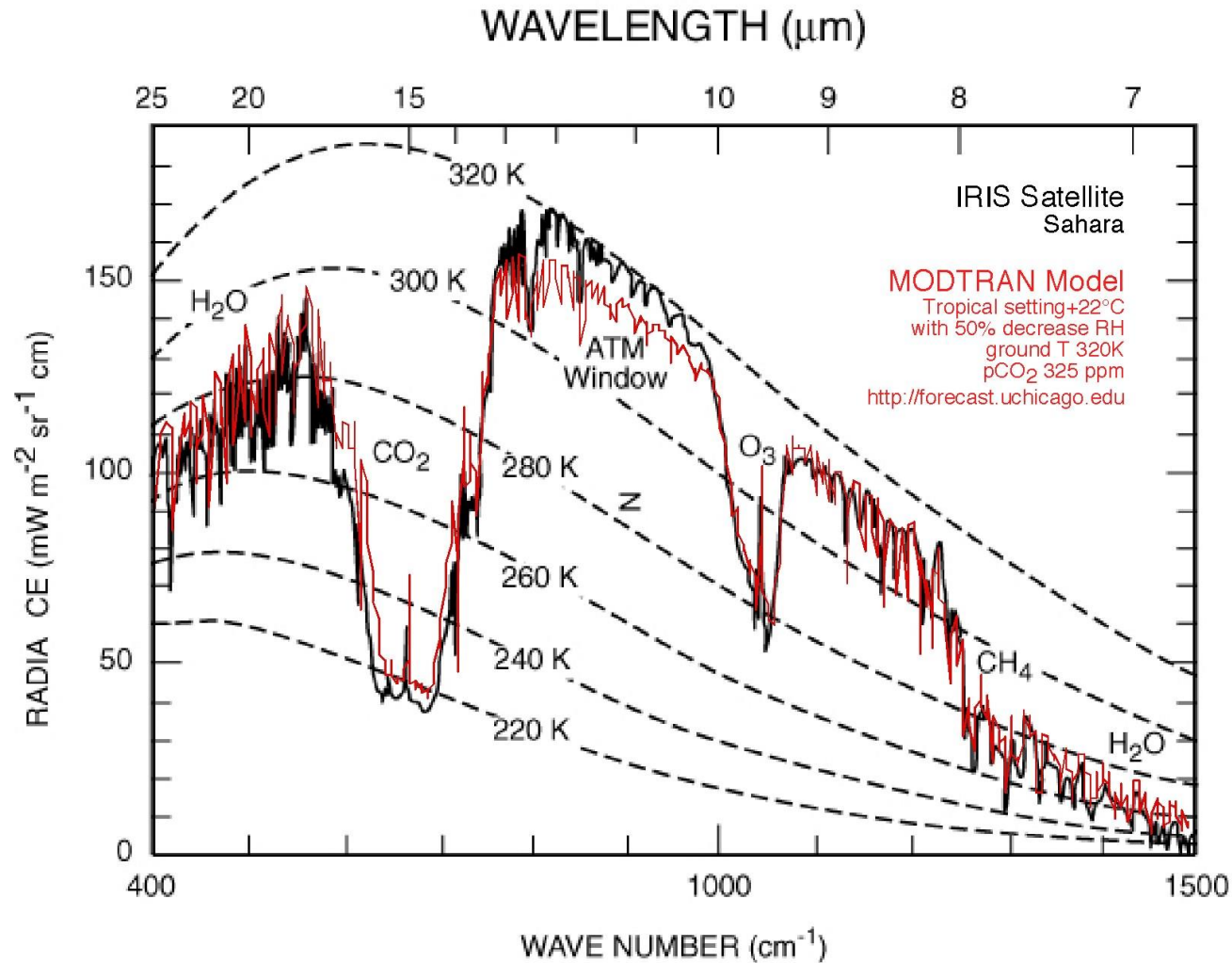
(Many believe it was creation of ozone in the atmosphere that allowed evolution of land dwellers – the water protected animals from UV radiation)



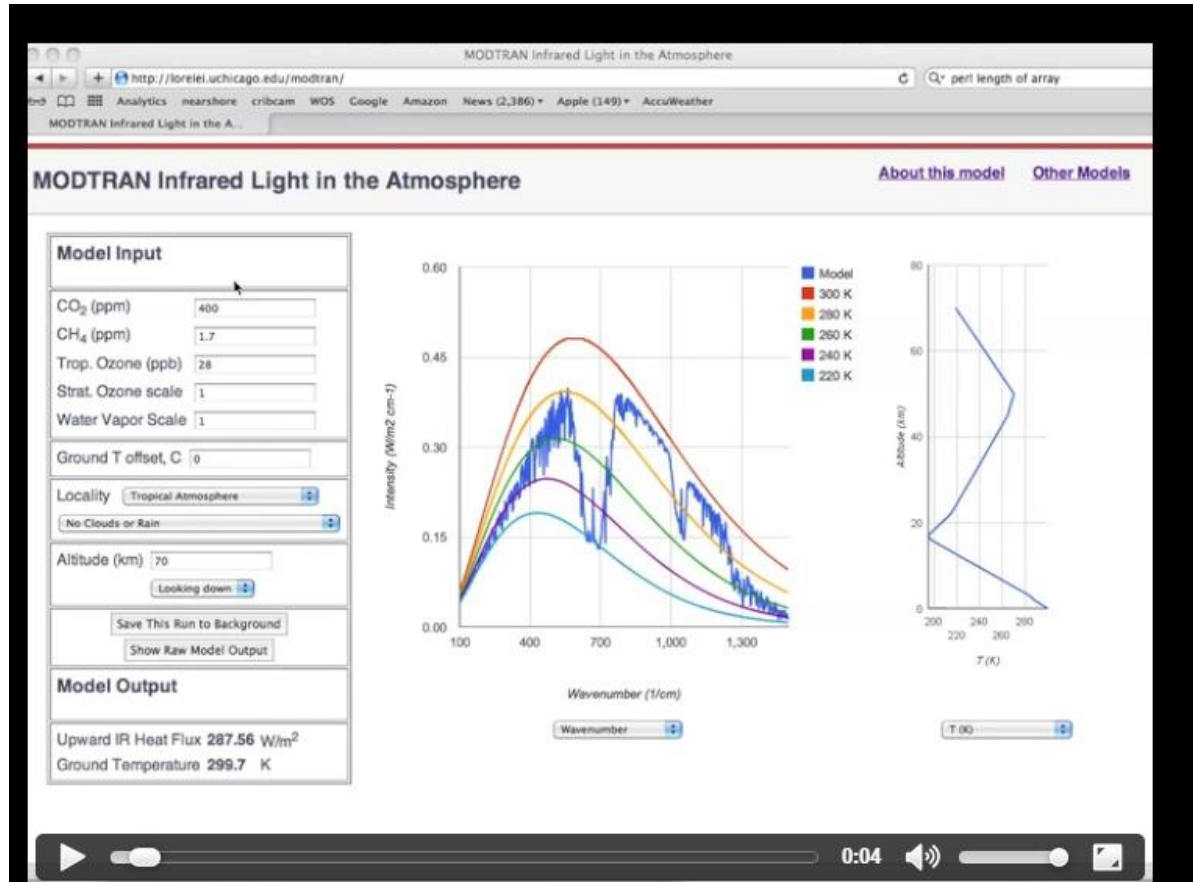
3. Oxygen and nitrogen, the two main components of the atmosphere absorb no IR radiation



## 4. Methane fills an open window in the absorption spectrum...



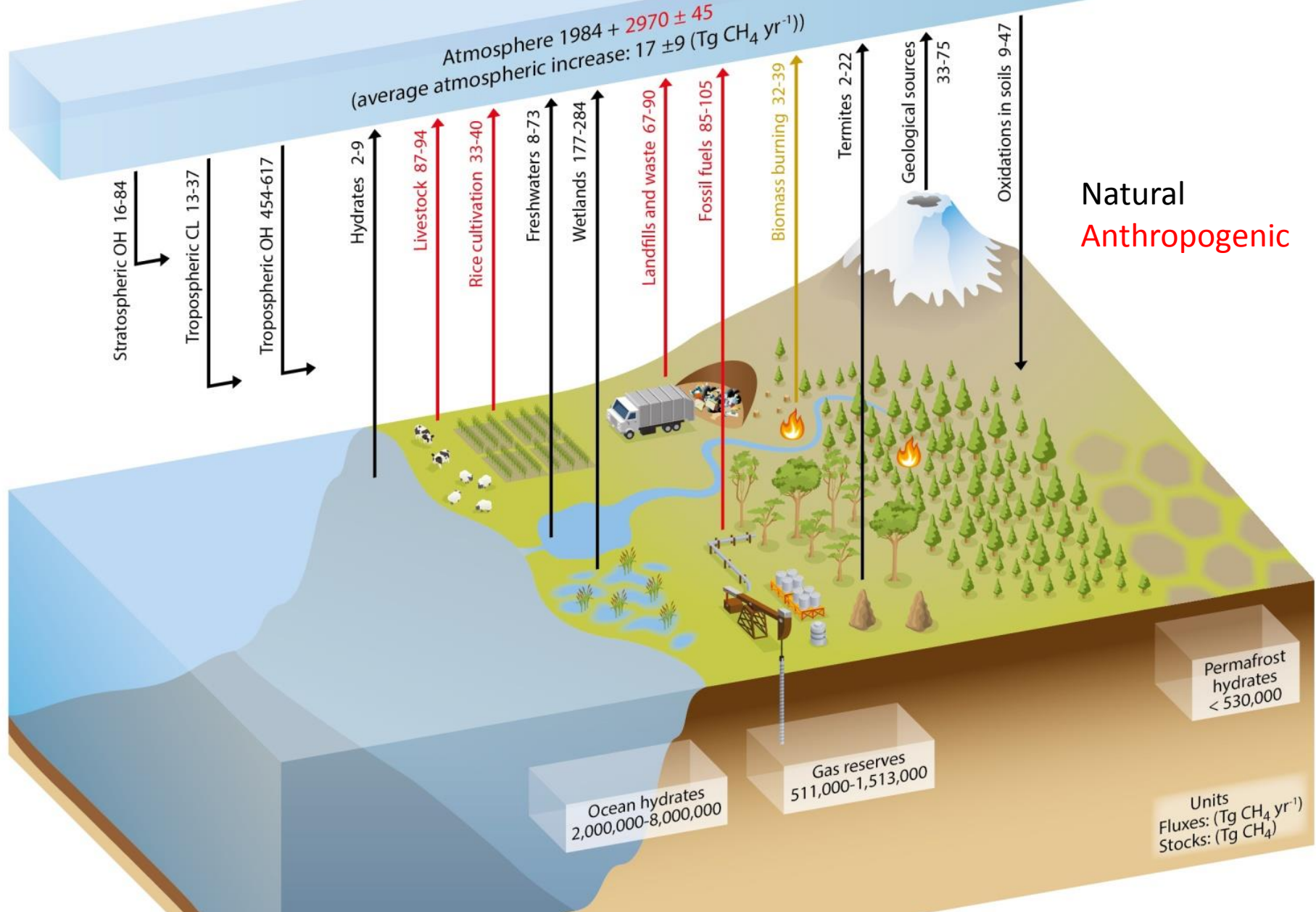
## Band 'saturation'



<http://climatemodels.uchicago.edu/modtran/modtran.mp4>



# Where is methane coming from?



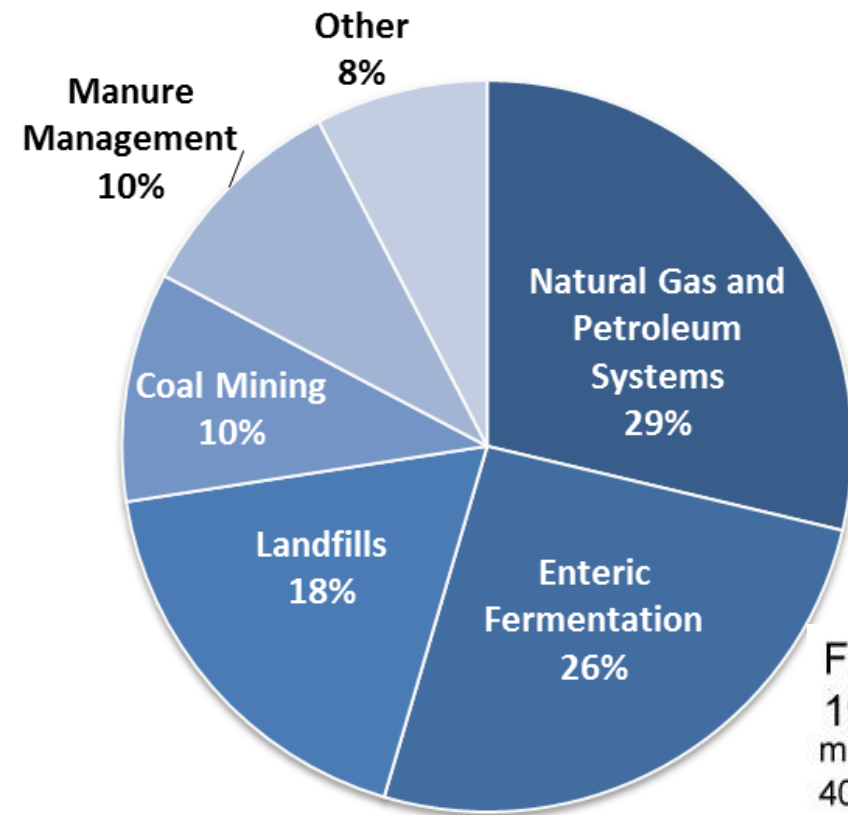


Figure 17. U.S. methane emissions by source, 1990-2009

million metric tons carbon dioxide equivalent

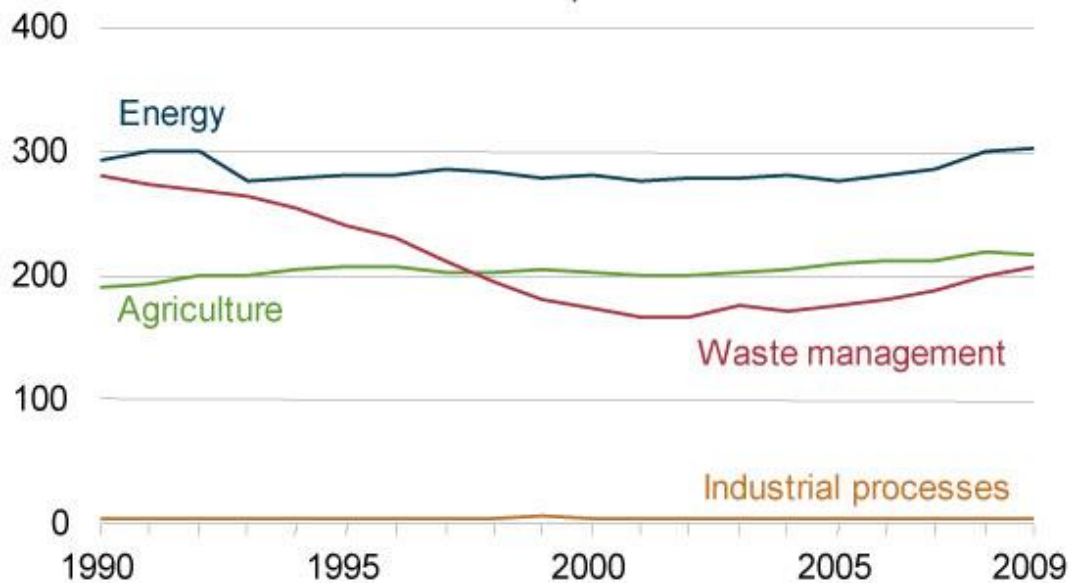
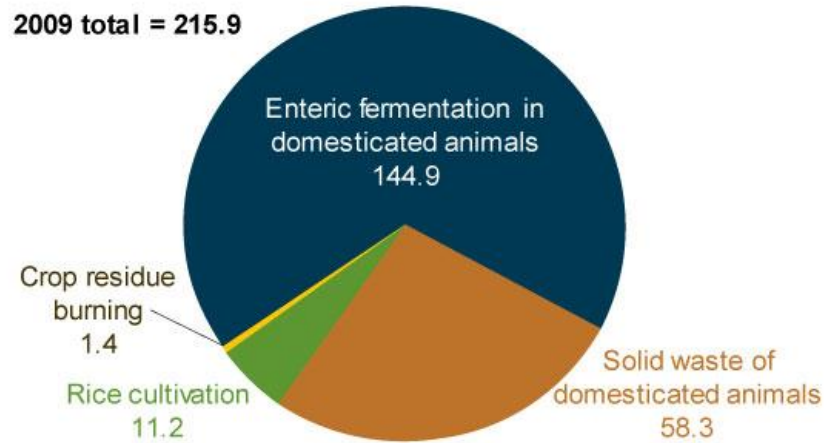




Figure 19. U.S. methane emissions from agriculture by source, 2009  
million metric tons carbon dioxide equivalent

2009 total = 215.9



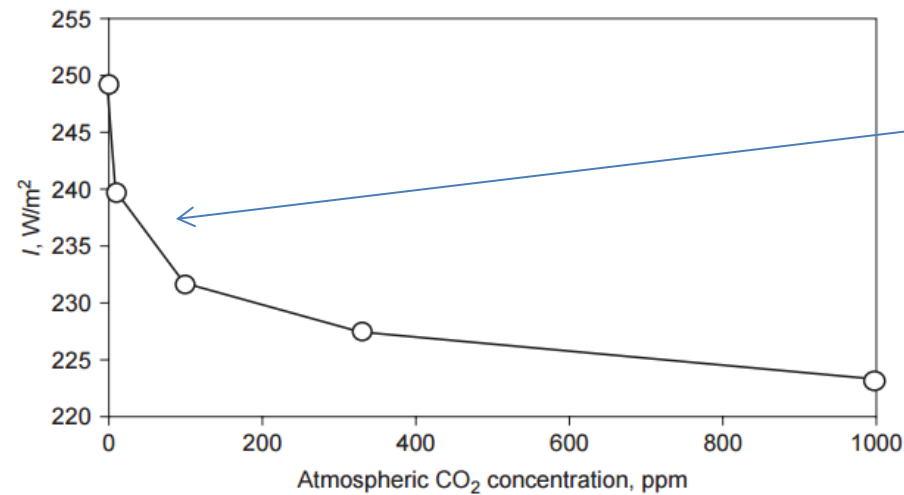
LIFE IS INFINITELY STRANGER  
THAN ANYTHING WHICH  
THE MIND OF MAN  
CAN INVENT



SHERLOCK HOLMES

## Difference in gases

- Because gases absorb IR selectively some radiation bands are completely absorbed.
- Others are '*atmospheric windows*'
  - This leads to higher greenhouse forcing per molecule for some gases.

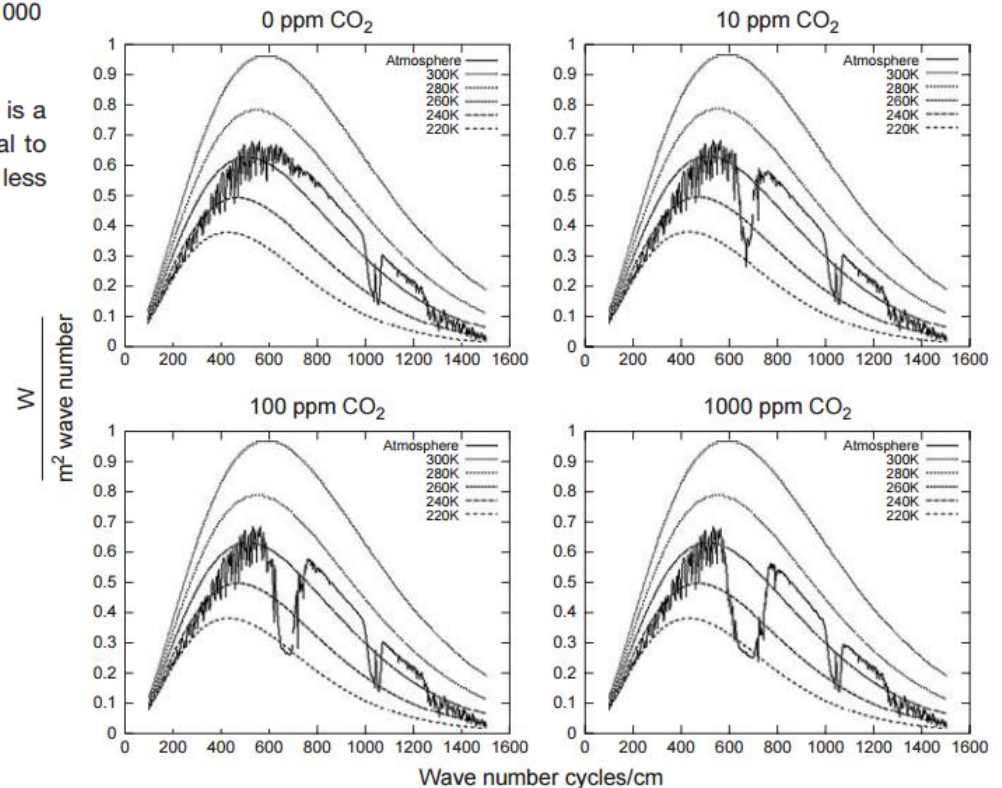


**Figure 4-6** Band saturation viewed in a different way from Figure 4-5. This is a plot of the total energy flux carried by all infrared light, which is proportional to the area under the spectrum curves in Figure 4-5. The outgoing energy flux is less sensitive to CO<sub>2</sub> when the CO<sub>2</sub> concentration is high.

Band can't get any deeper, as the bottom is defined by the temperature of the atmosphere.

The band widens with increasing concentration.

This same relationship is true of CH<sub>4</sub> methane (and other gases) which is why adding one molecule of CH<sub>4</sub> creates ~25-75x the effect as adding one molecule of CO<sub>2</sub>




**Figure 4-5** A demonstration of band saturation by CO<sub>2</sub>. The addition of 10 ppm CO<sub>2</sub> (upper right) makes a huge difference to the outgoing infrared light spectrum relative to an atmosphere that has no CO<sub>2</sub> (upper left). Increasing CO<sub>2</sub> to 100 and 1,000 ppm (lower panels) continues to affect the spectrum, but you get less bang for your CO<sub>2</sub> buck as CO<sub>2</sub> concentration gets higher.

Because of the band saturation issue,

- A molecule of  $\text{CH}_4$  methane added to the atmosphere is about 25-75 times more powerful than is a molecule of  $\text{CO}_2$   
(25-75x depending on time frame considered)

**GWP (global warming potential) is defined as the total radiative forcing (i.e. heating) over 100 years or another time horizon caused by emitting a gas (such as methane), compared to emitting an equal amount of CO<sub>2</sub>.**

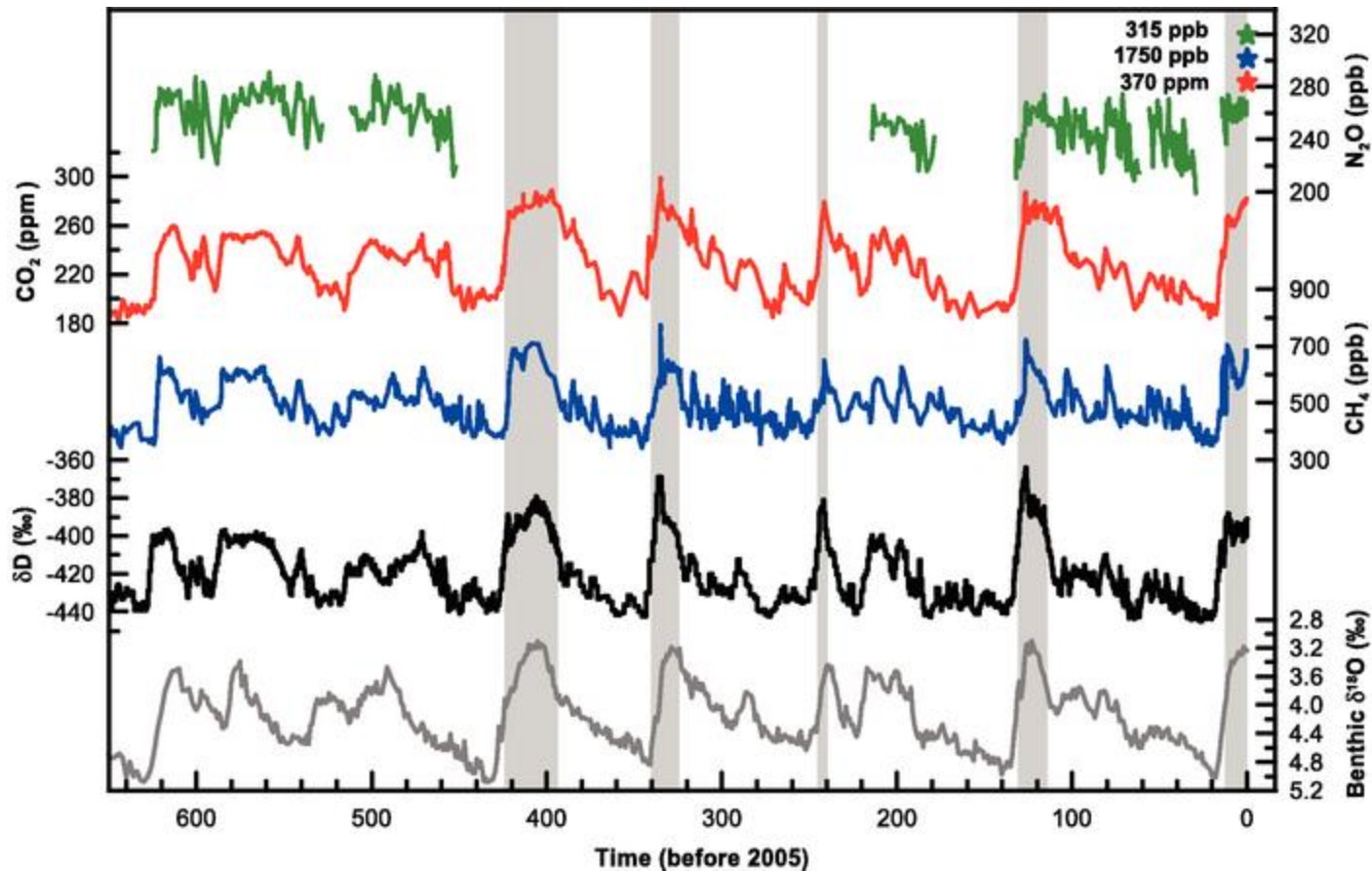
CH<sub>4</sub> has a relatively short residence time of 10 years in the atmosphere which is why it has greatest GWP over the shorter time horizon



Greenhouse Gas	GWP After 20 Years	GWP After 100 Years
Carbon Dioxide	1	1
Methane	72	25
Nitrous Oxide	289	298
HCFC-22	5160	1810
HFC-23	12000	14800
HFC-125	6350	3500
HFC-134a	3830	1430
HFC-143a	5890	4470
CF <sub>4</sub>	5210	7390
C <sub>2</sub> F <sub>6</sub>	8630	12200
SF <sub>6</sub>	16300	22800

(We are investigating methane as an example, you can see that the fluorinated gases (all are made by humans) have enormous GWP. Although the Montreal Protocol regulates the phasing out of HCFCs, there is currently no international agreement on the regulation of HFCs. Efforts are ongoing to develop a global approach...)





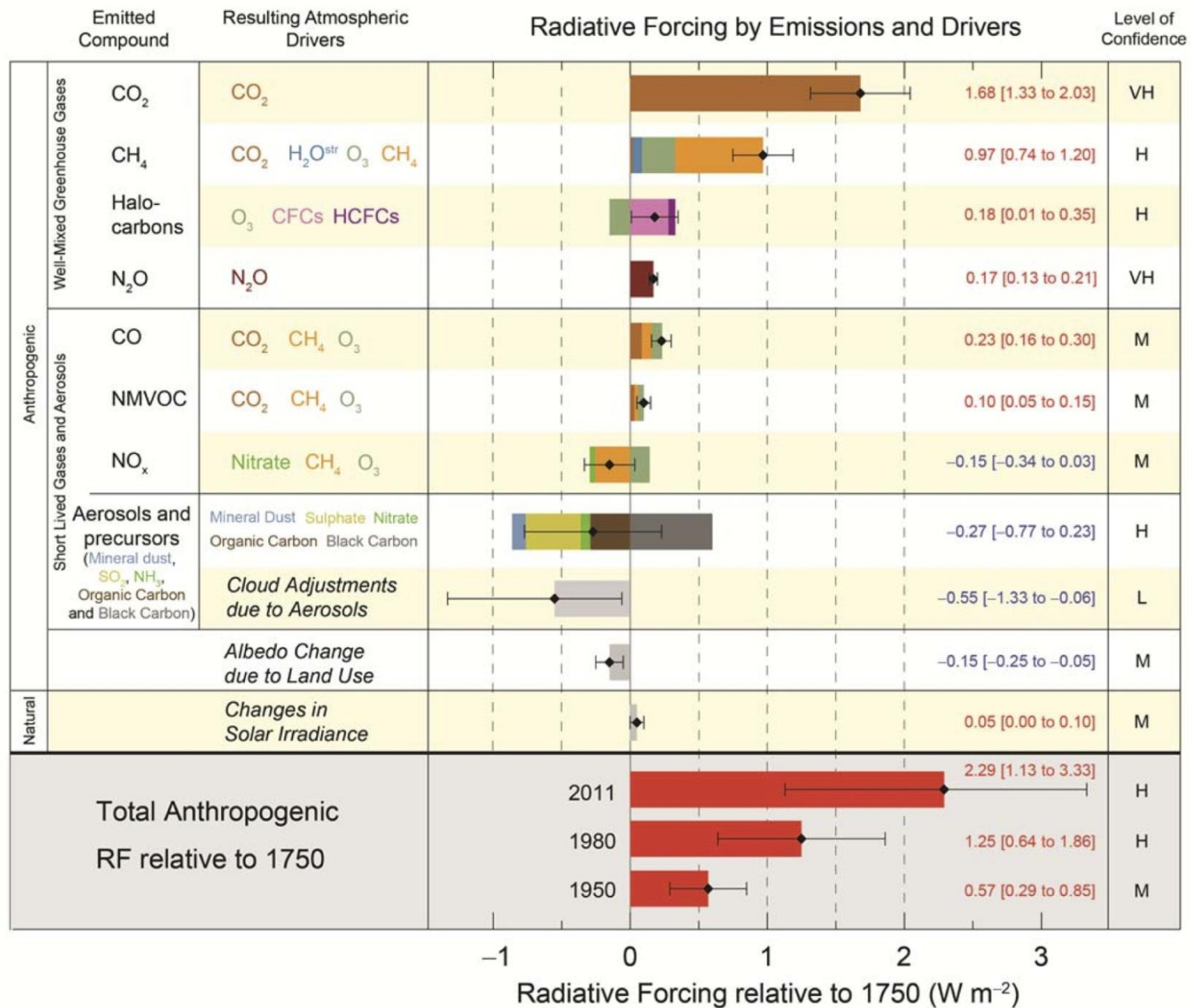
*Ice core and ocean sediment core data. Grey bars represent interglacial periods. The stars and labels indicate atmospheric concentrations at year 2000.*

## 5. And, yes, carbon dioxide does absorb IR radiation



Iain Stewart demonstrates infrared radiation absorption by CO<sub>2</sub>


<https://www.youtube.com/watch?v=Ot5n9m4whaw>



<http://climatemodels.uchicago.edu/sluggulator/sluggulator.html>

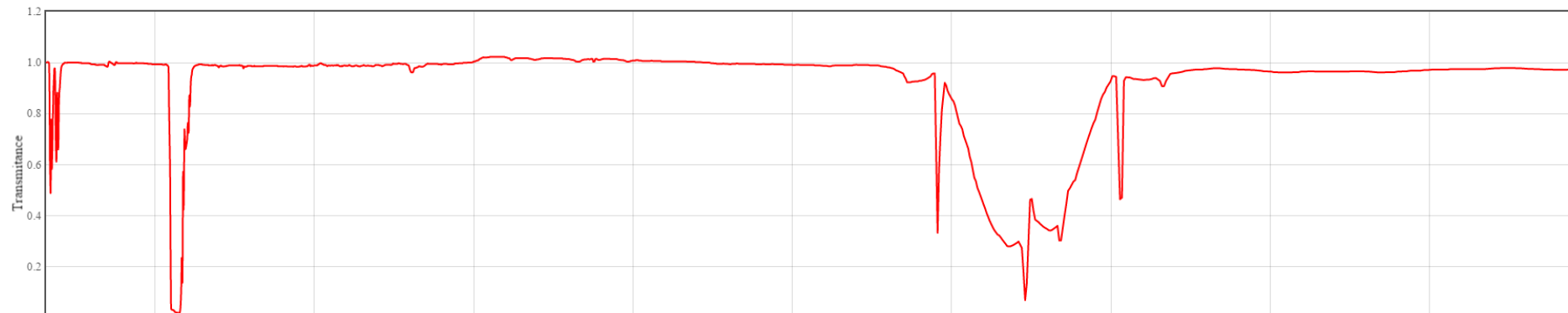


WHEN  
YOU HAVE  
ELIMINATED THE  
IMPOSSIBLE  
.....  
WHATEVER REMAINS  
.....  
HOWEVER IMPROBABLE  
MUST BE THE  
TRUTH  
SHERLOCK HOLMES

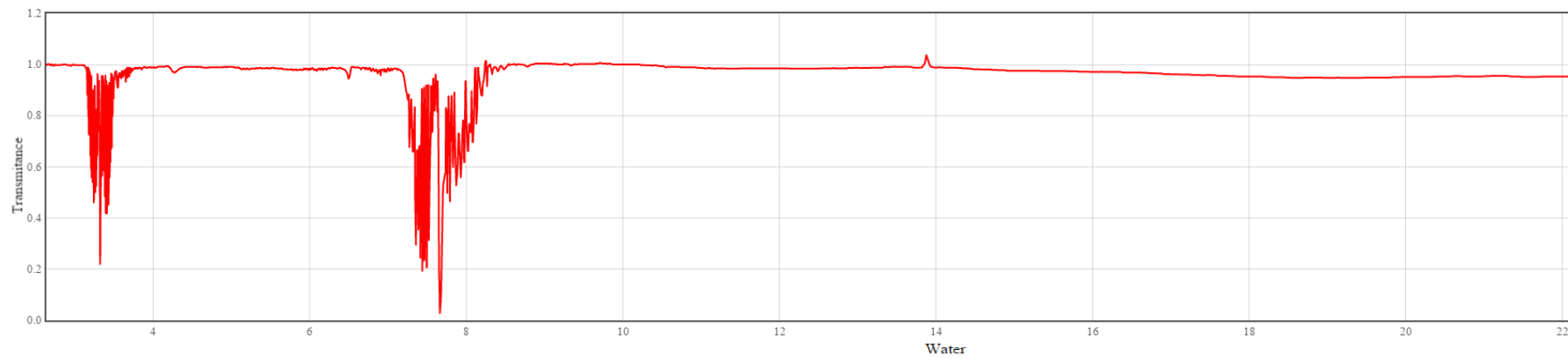


<http://www.epa.gov/climatechange/science/causes.html#>

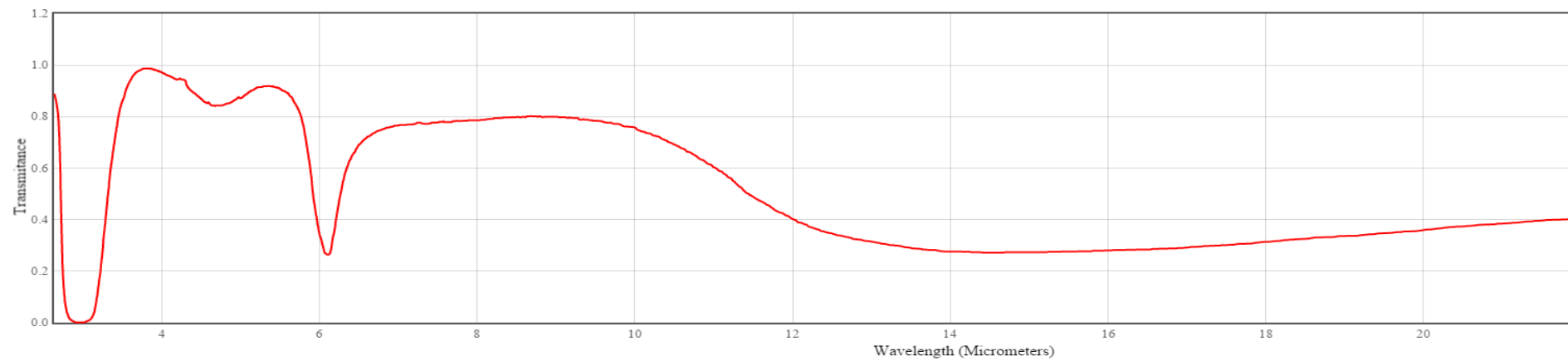
Carbon Dioxide  
Infrared Spectrum

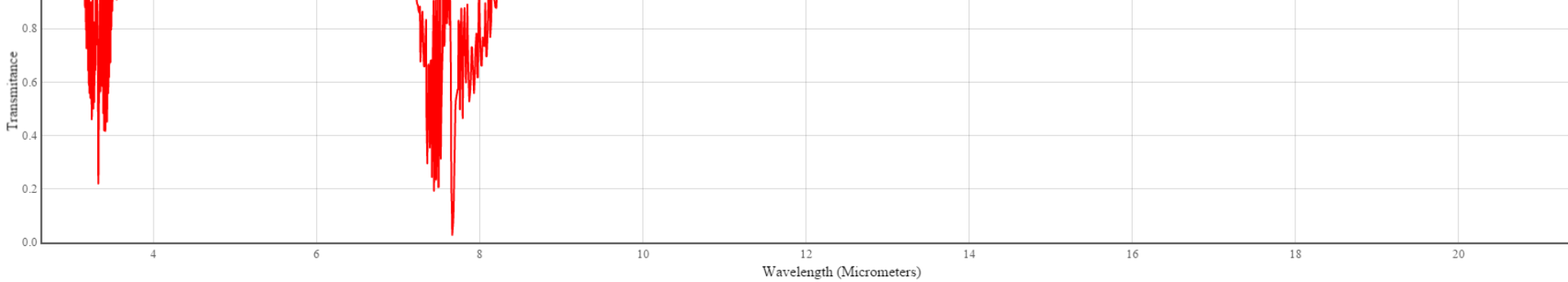


Methane  
Infrared Spectrum

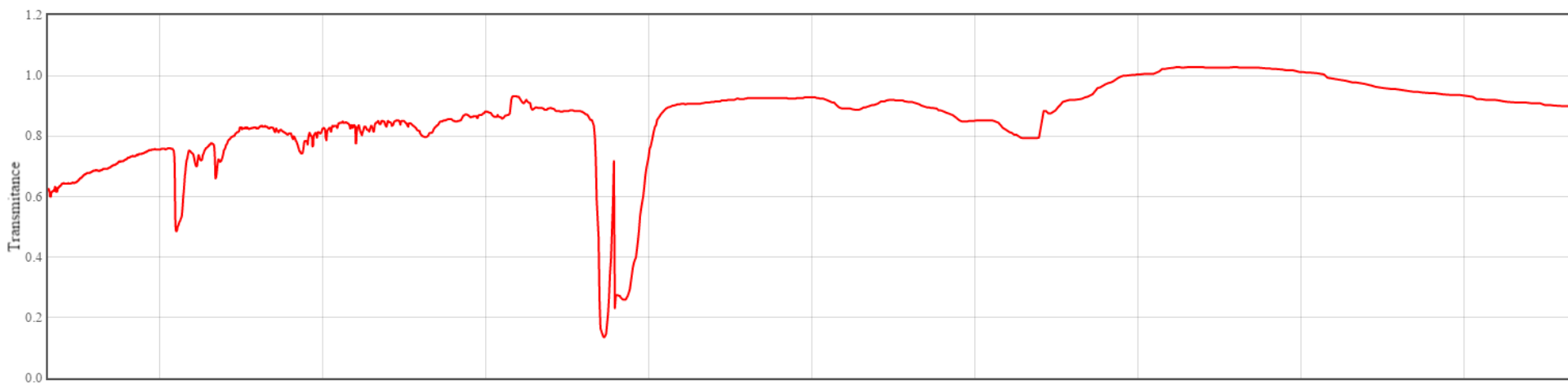


Water  
Infrared Spectrum

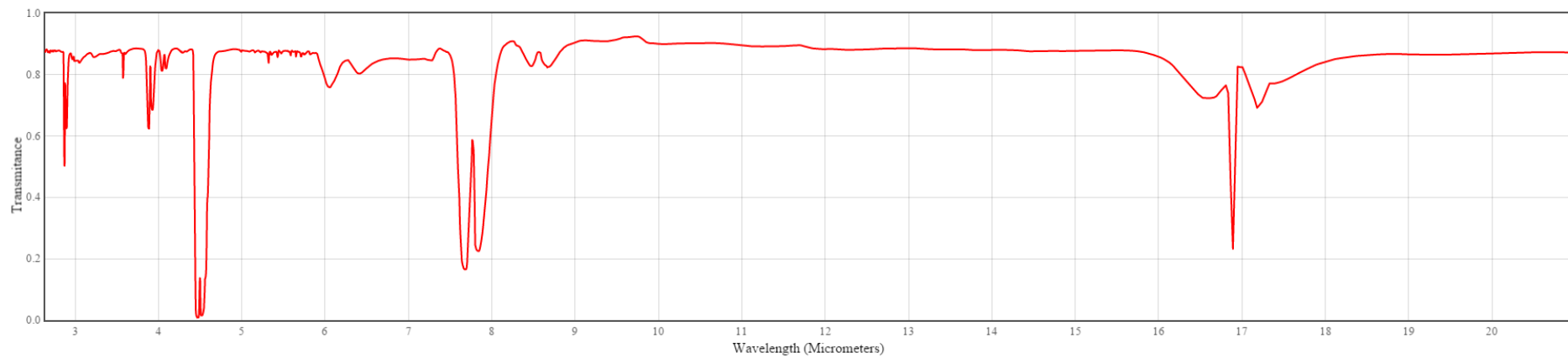




Ozone  
Infrared Spectrum

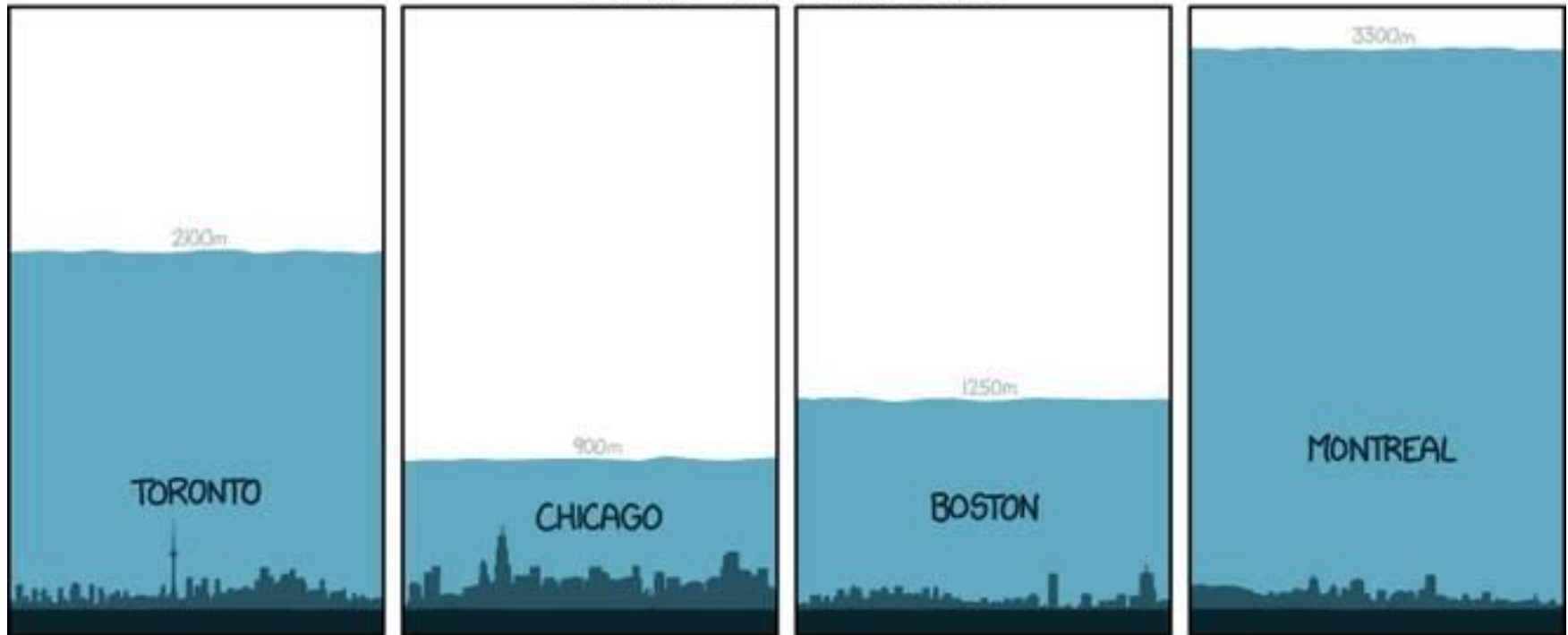


Nitrous oxide  
Infrared Spectrum



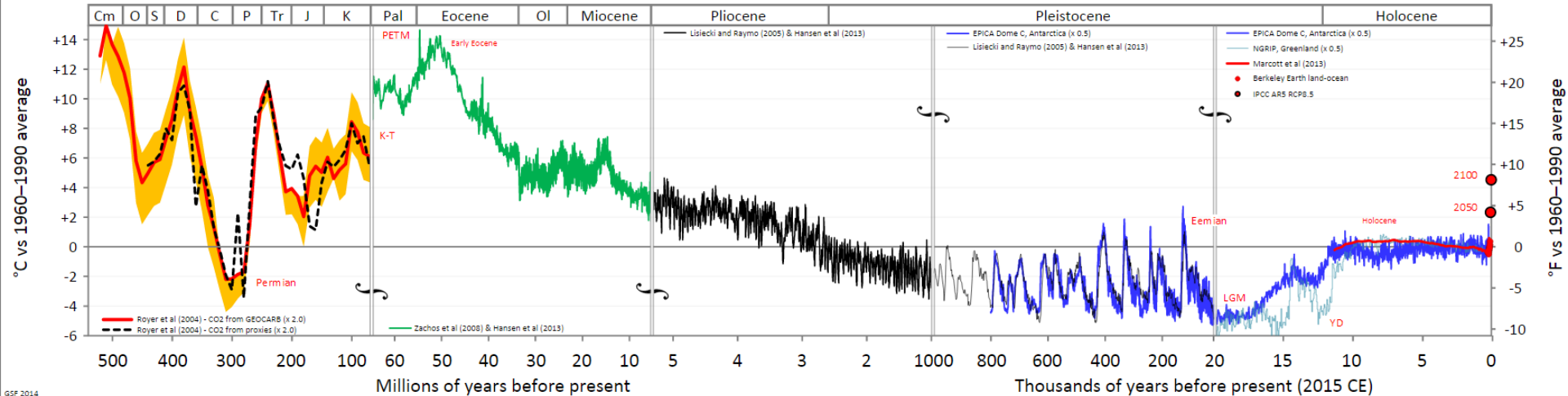
A geologists perspective:

# THICKNESS OF THE ICE SHEETS AT VARIOUS LOCATIONS 21,000 YEARS AGO COMPARED WITH MODERN SKYLINES



# Are current temperatures the highest earth has ever seen?

Temperature of Planet Earth



Not even close....

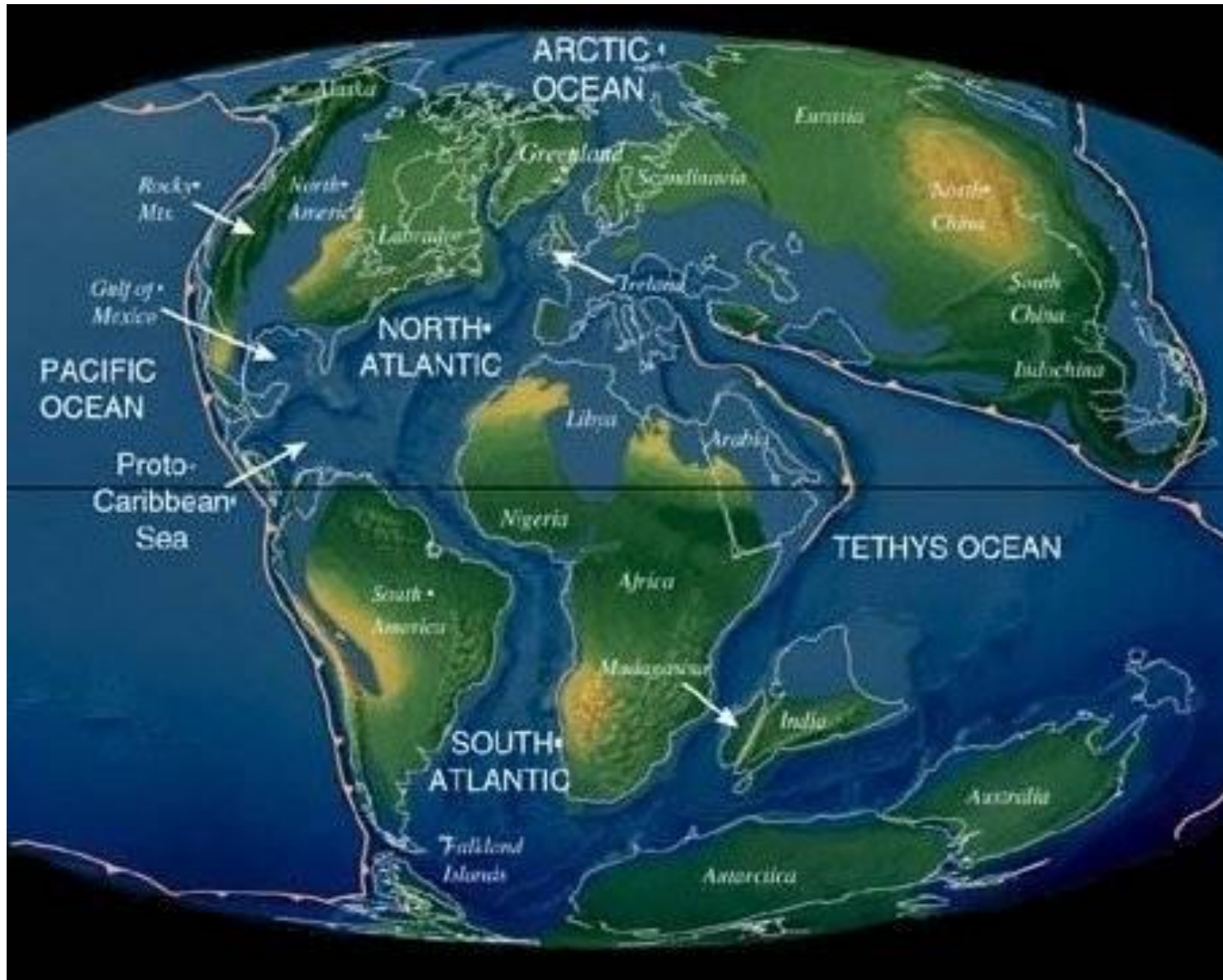
(but they are the highest modern creatures/plants have seen)

'There is nothing new under the sun. It has all been done before.'

Sherlock Holmes

-*A Study in Scarlet*

Cretaceous  
(145 – 65 MYA)  
paleo-map

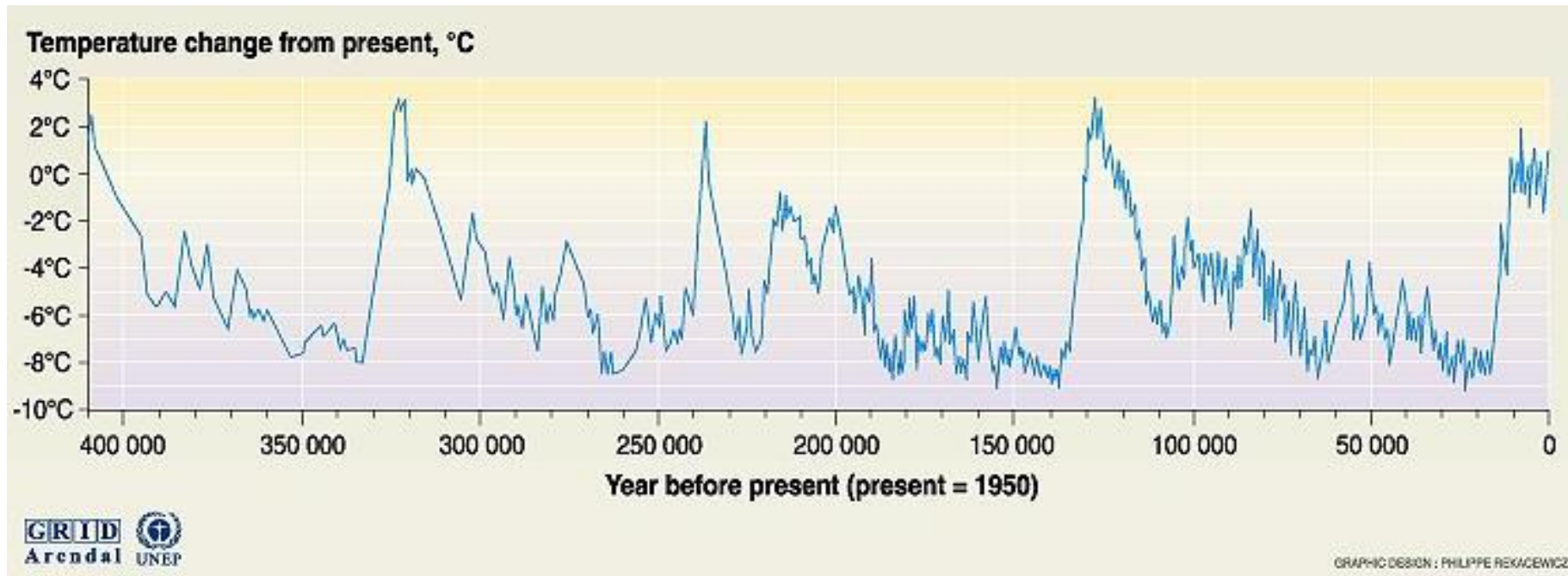


...100 million years ago it was much hotter....  
30% more land surface was covered with water!  
(CO<sub>2</sub> was 2-4x what we have today)



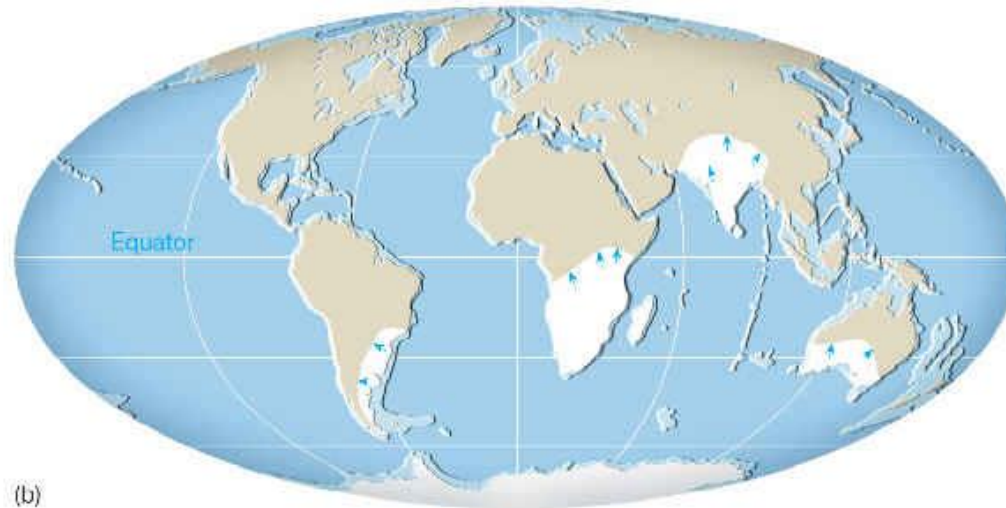
Ok, so global temperatures have fluctuated over earth's history...but why?

And why so cyclical?



Source: J.R. Petit, J. Jouzel, et al. Climate and atmospheric history of the past 420 000 years from the Vostok ice core in Antarctica, *Nature* 399 (3 June), pp 429-436, 1999.

# 1. Plate tectonics

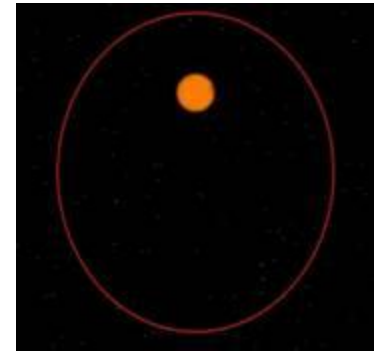


(time scale = **millions of years**...so what about variations on smaller time scales like tens of thousands of years, i.e. our glacial/interglacial periods?)

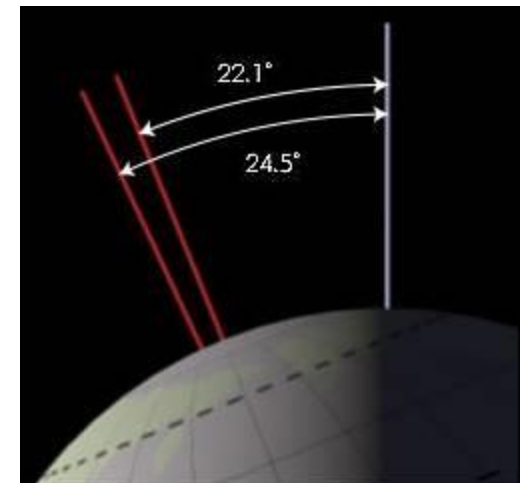


## 2. Milankovitch Cycles

- variations in shape of *earth's orbit* (**eccentricity**)
  - as orbit becomes more elliptical, seasonal heating and cooling is more pronounced



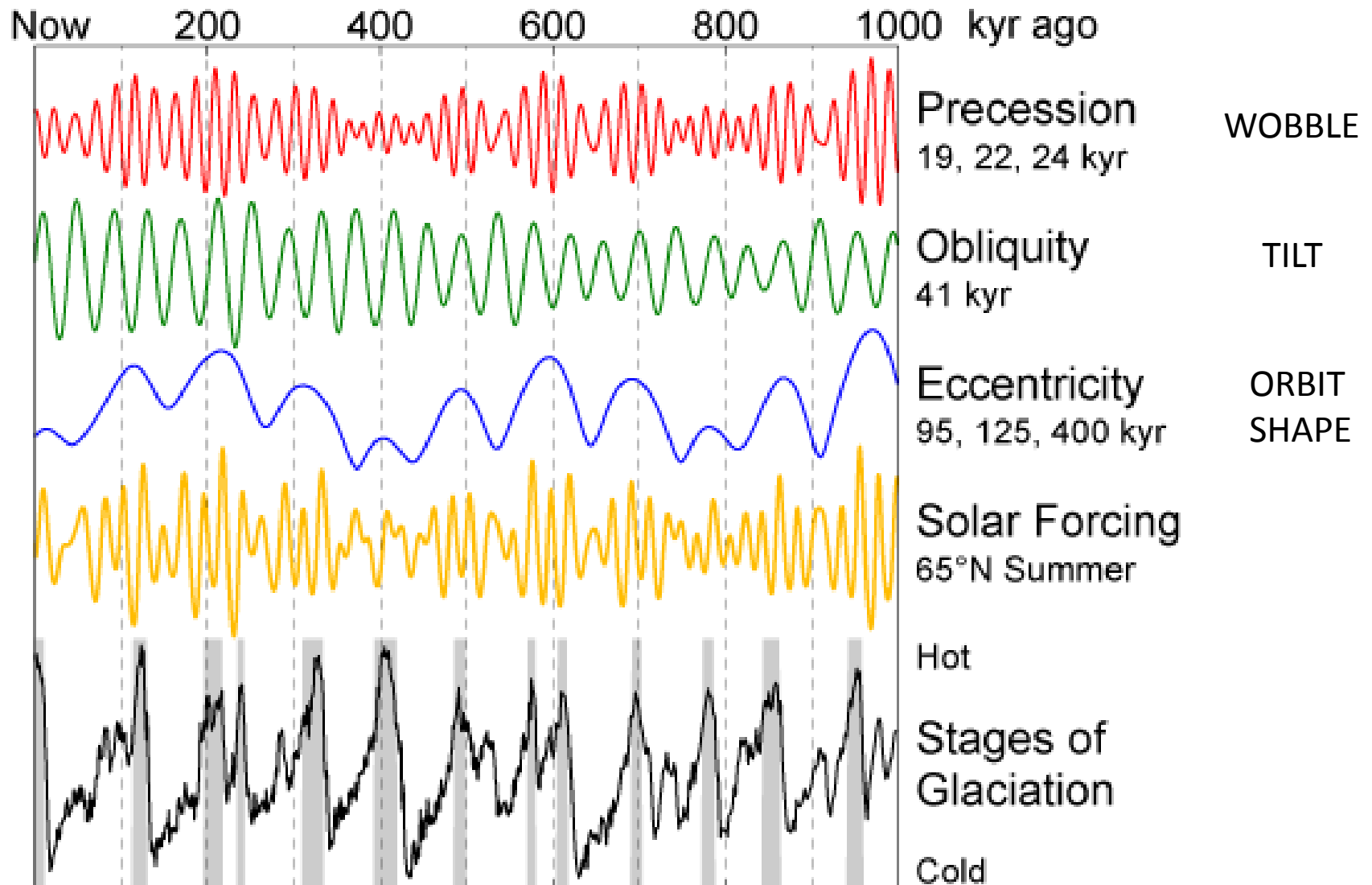
- variations in earth's *tilt angle* (**obliquity**)
  - increases seasonal variation at high latitudes



- wobbling of earth's *axis* (**precession**)
  - affects when seasons begin

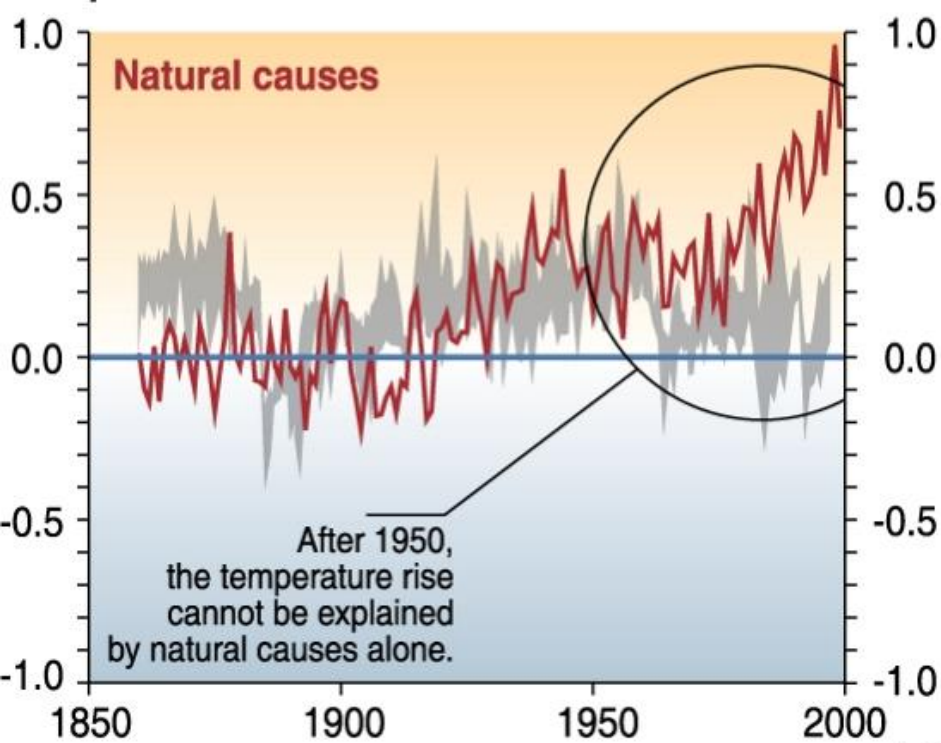


**The combined effect results in glacial/interglacial periodicity of ~100,000 years**

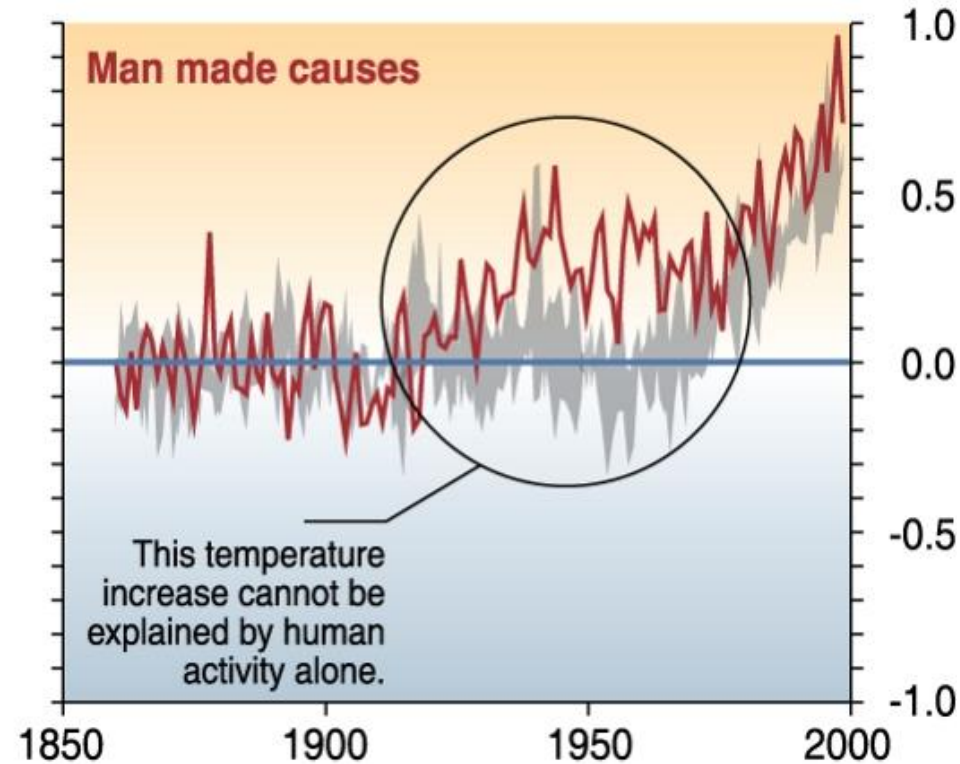


## Comparison between modeled and observed temperature since 1860

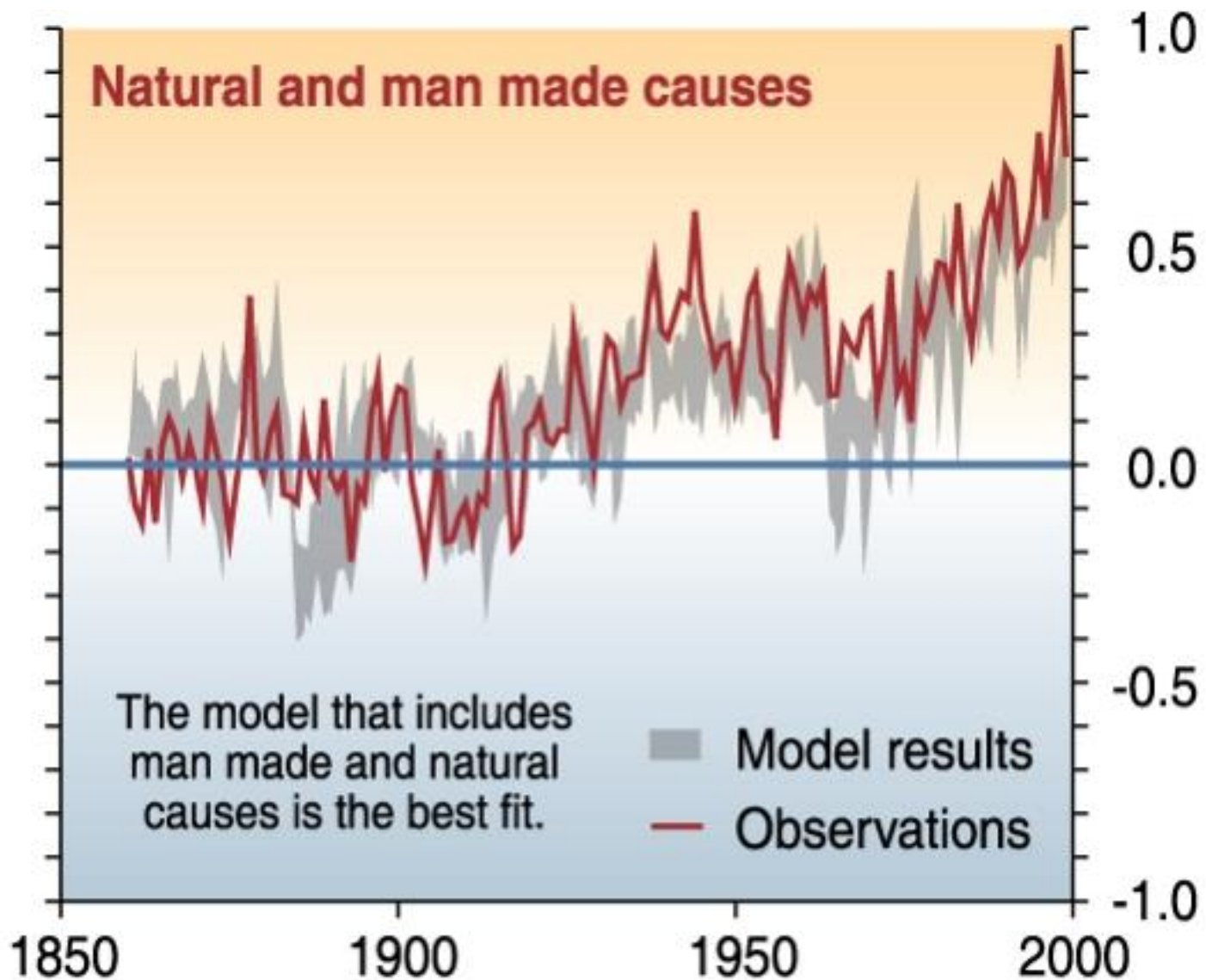
Temperature anomalies in °C



**So are current warming trends just part of natural cycles?**



Computer models based on our best understanding of processes that control climate



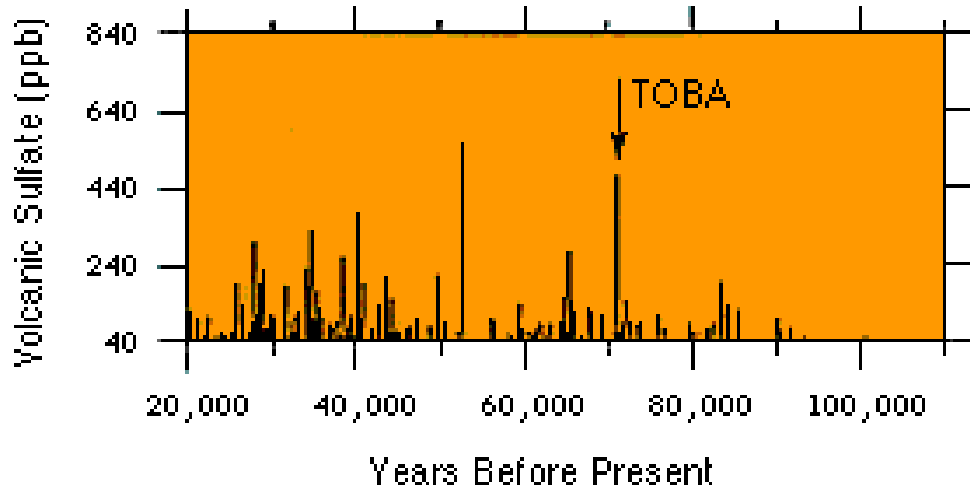


How do we measure the gases that were in the atmosphere tens of thousands of years ago?



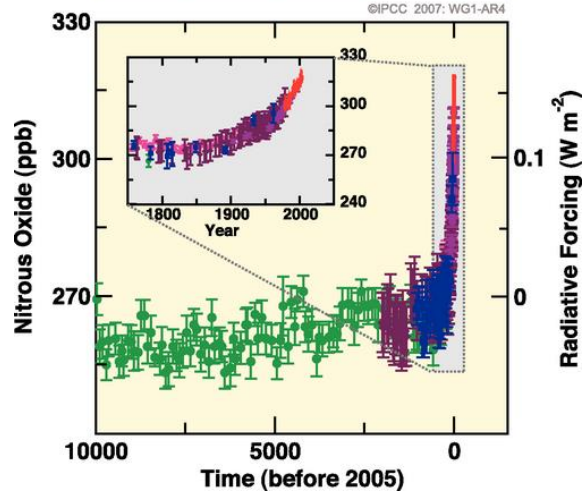
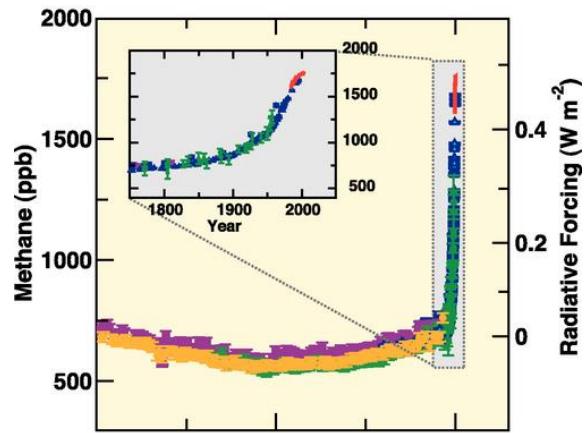
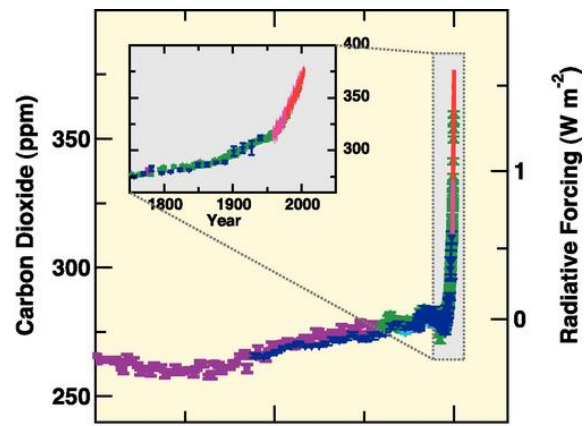
Ice cores can provide atmospheric gas/dust/aerosol data for approximately the past 1 million years – beyond that we depend on the geologic record to approximate climate (through geologic record and stable isotope data)





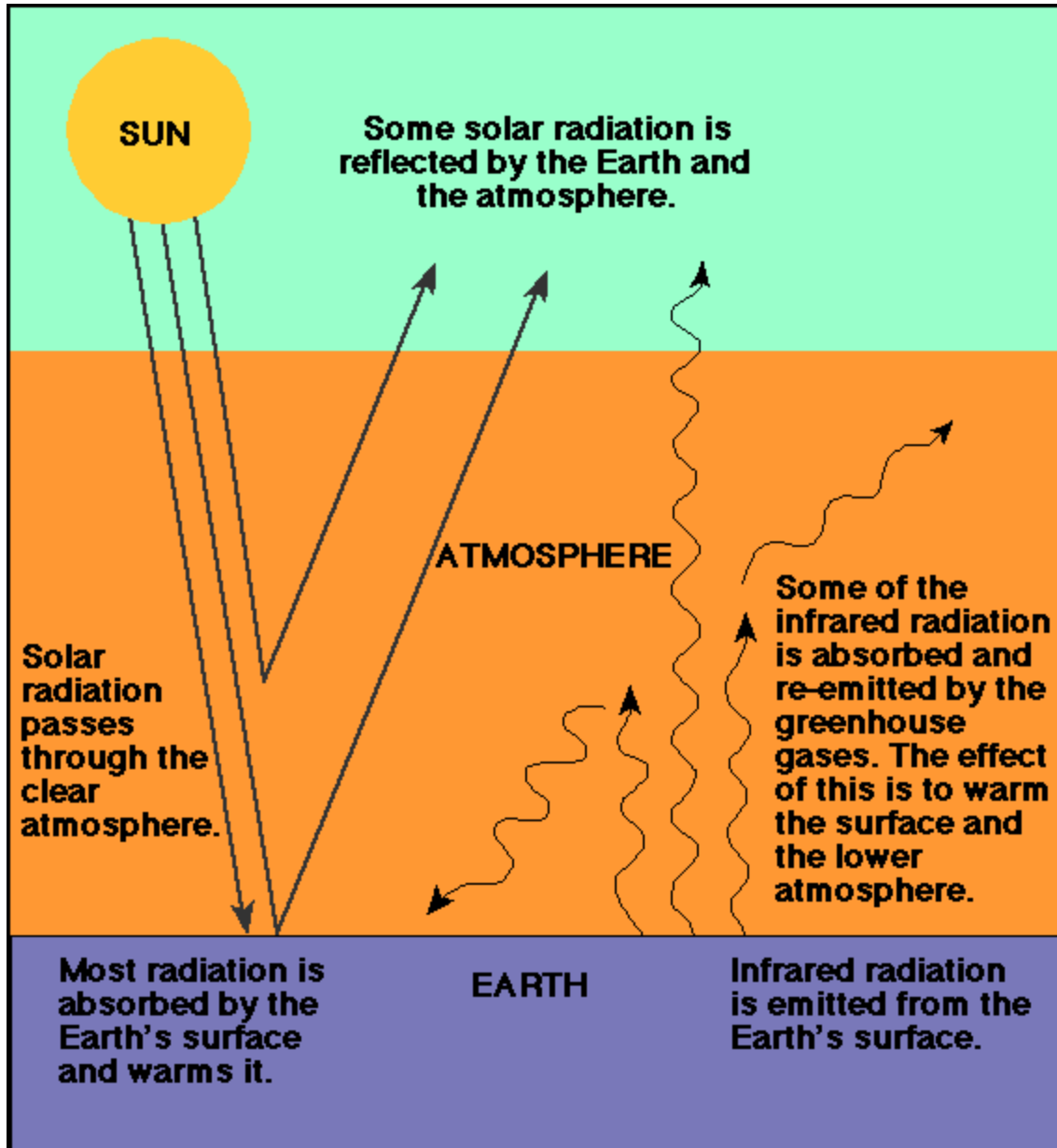
**Evidence of past eruptions**  
 (Toba was the largest eruption in the past 500,000 years)

# Gas data collected from ice cores



©IPCC 2007: WG1-AR4

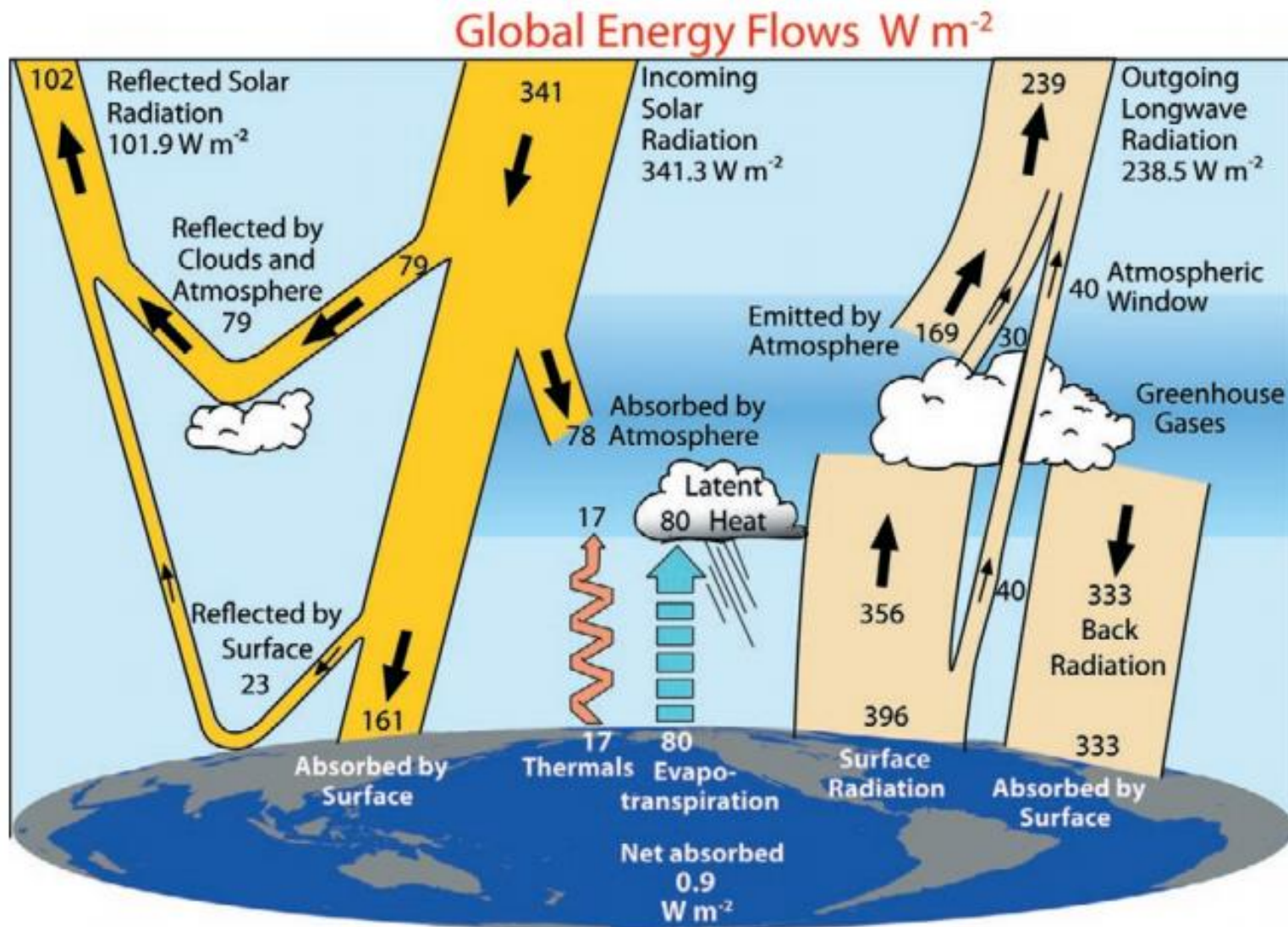
# Greenhouse Effect



(GHG are not all bad -- without any GHGs earth would be 33° C colder!)

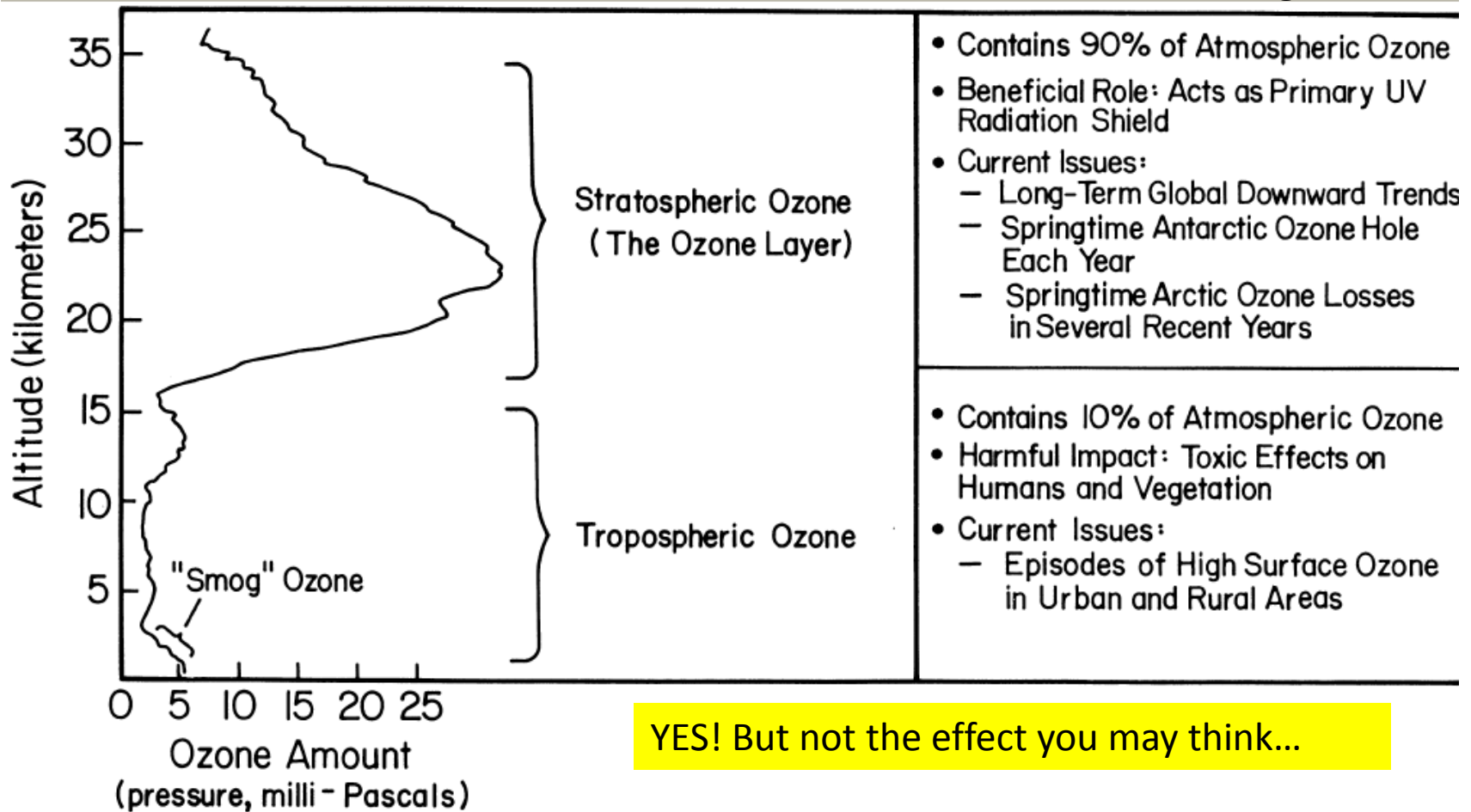






**FIG. 1.** The global annual mean Earth's energy budget for the Mar 2000 to May 2004 period ( $\text{W m}^{-2}$ ). The broad arrows indicate the schematic flow of energy in proportion to their importance.

What about the hole in the ozone? Doesn't it have an effect on warming?

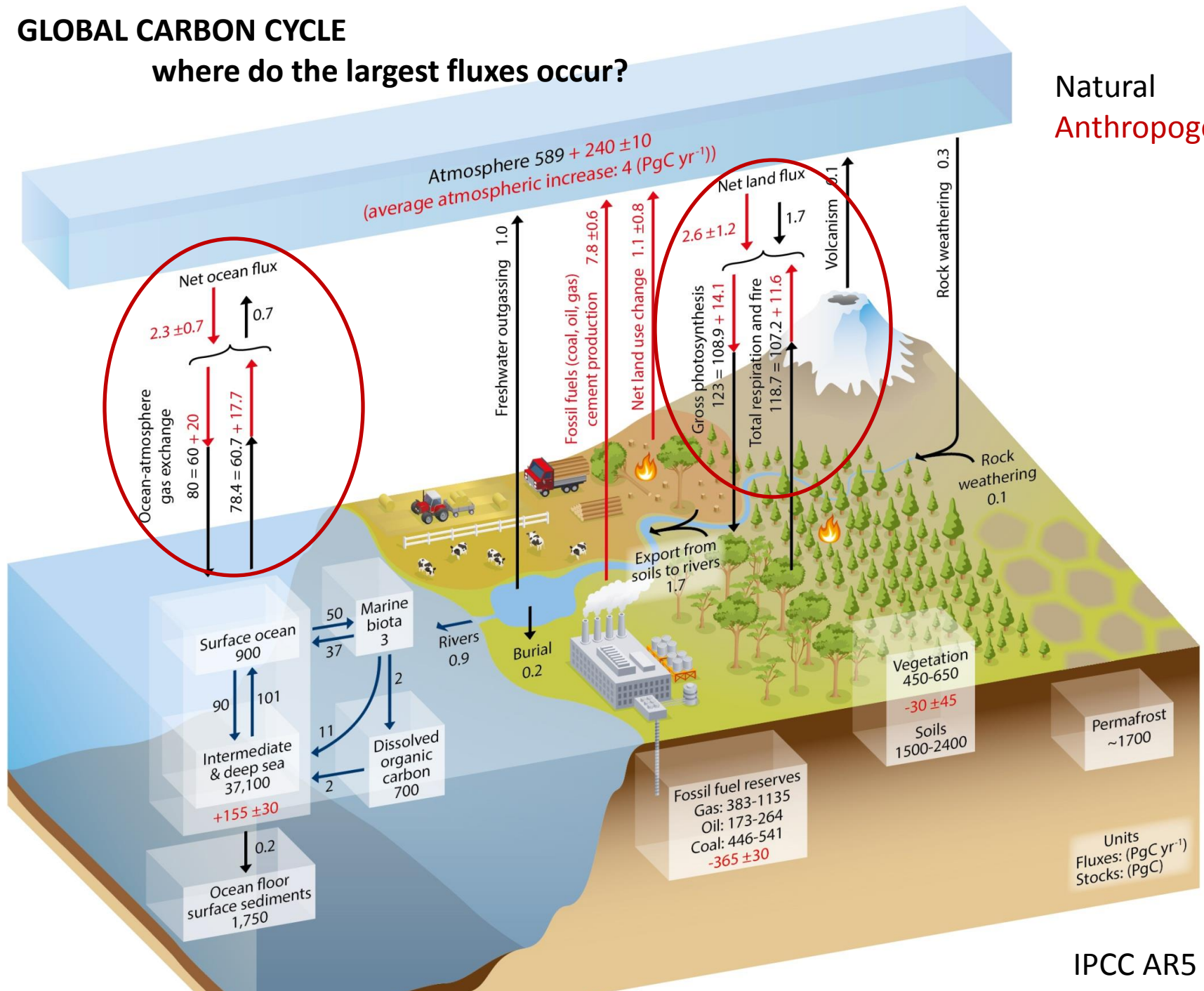


Ozone generates heat in the stratosphere, both by absorbing the sun's ultraviolet radiation and by absorbing upwelling infrared radiation from the lower atmosphere (troposphere). Consequently, decreased ozone in the stratosphere results in lower temperatures. Observations show that over recent decades, the mid to upper stratosphere (from 30 to 50 km above the Earth's surface) has cooled by 1° to 6° C (2° to 11° F). This stratospheric cooling has taken place at the same time that greenhouse gas amounts in the lower atmosphere (troposphere) have risen.

# GLOBAL CARBON CYCLE

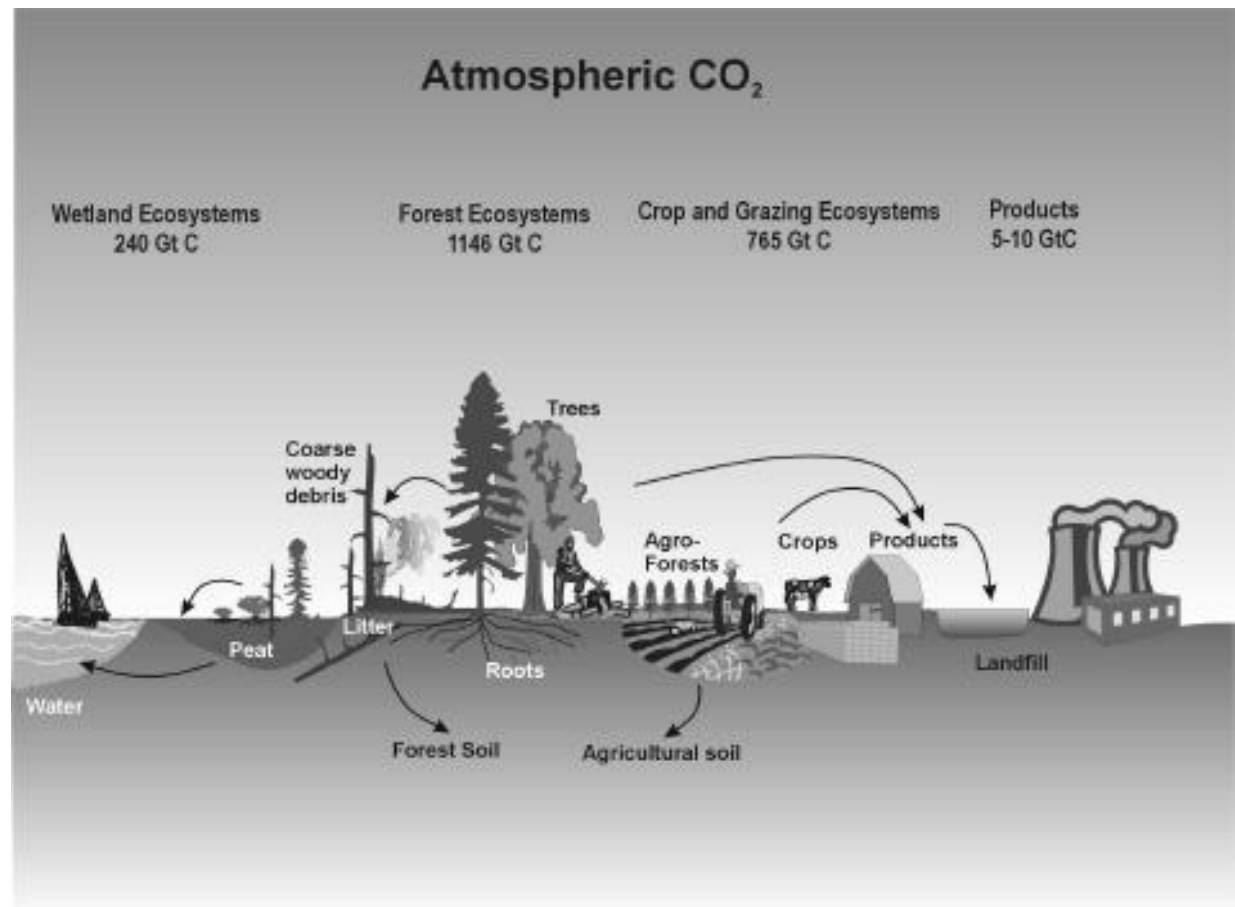
where do the largest fluxes occur?

Natural  
Anthropogenic

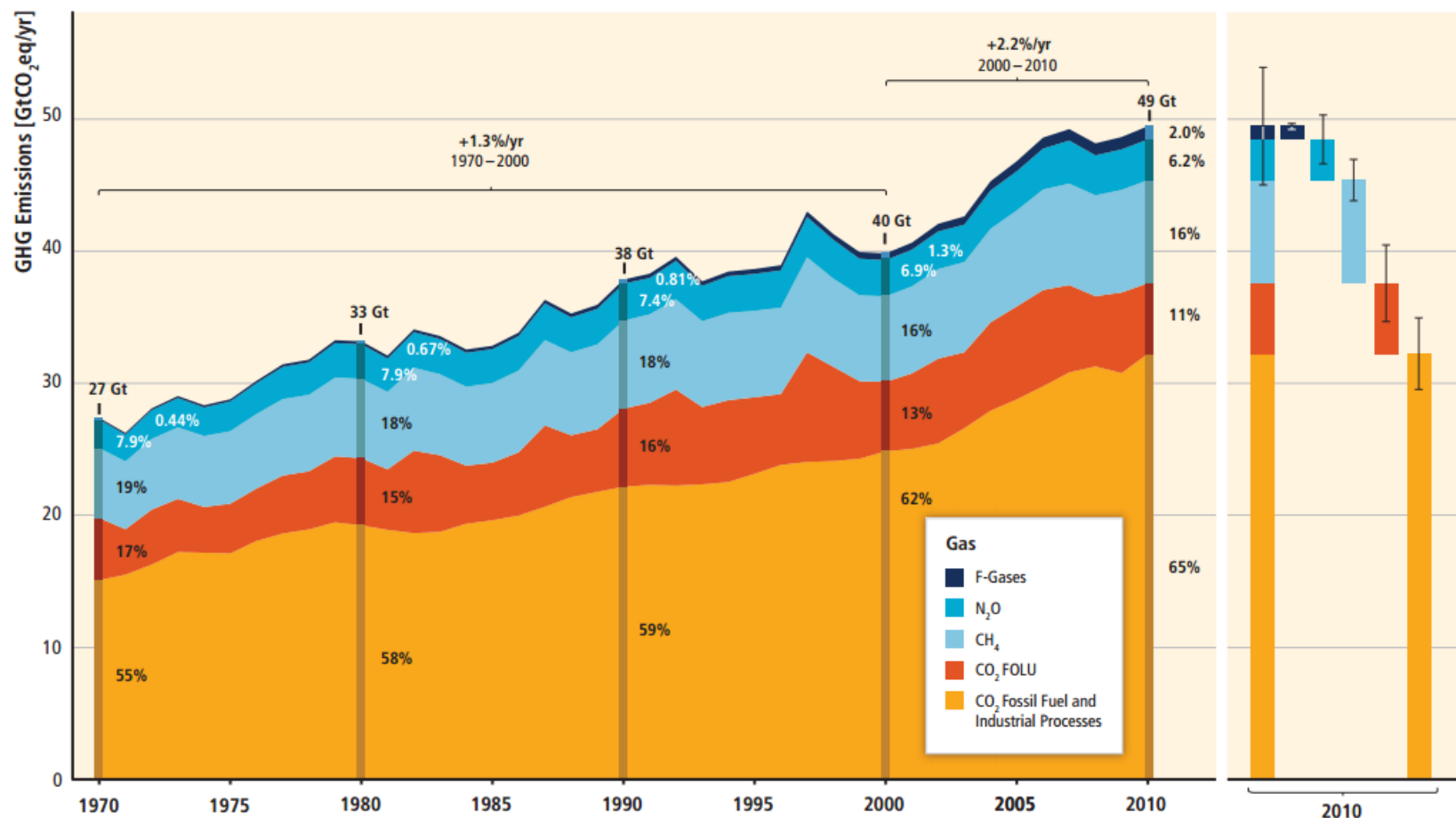




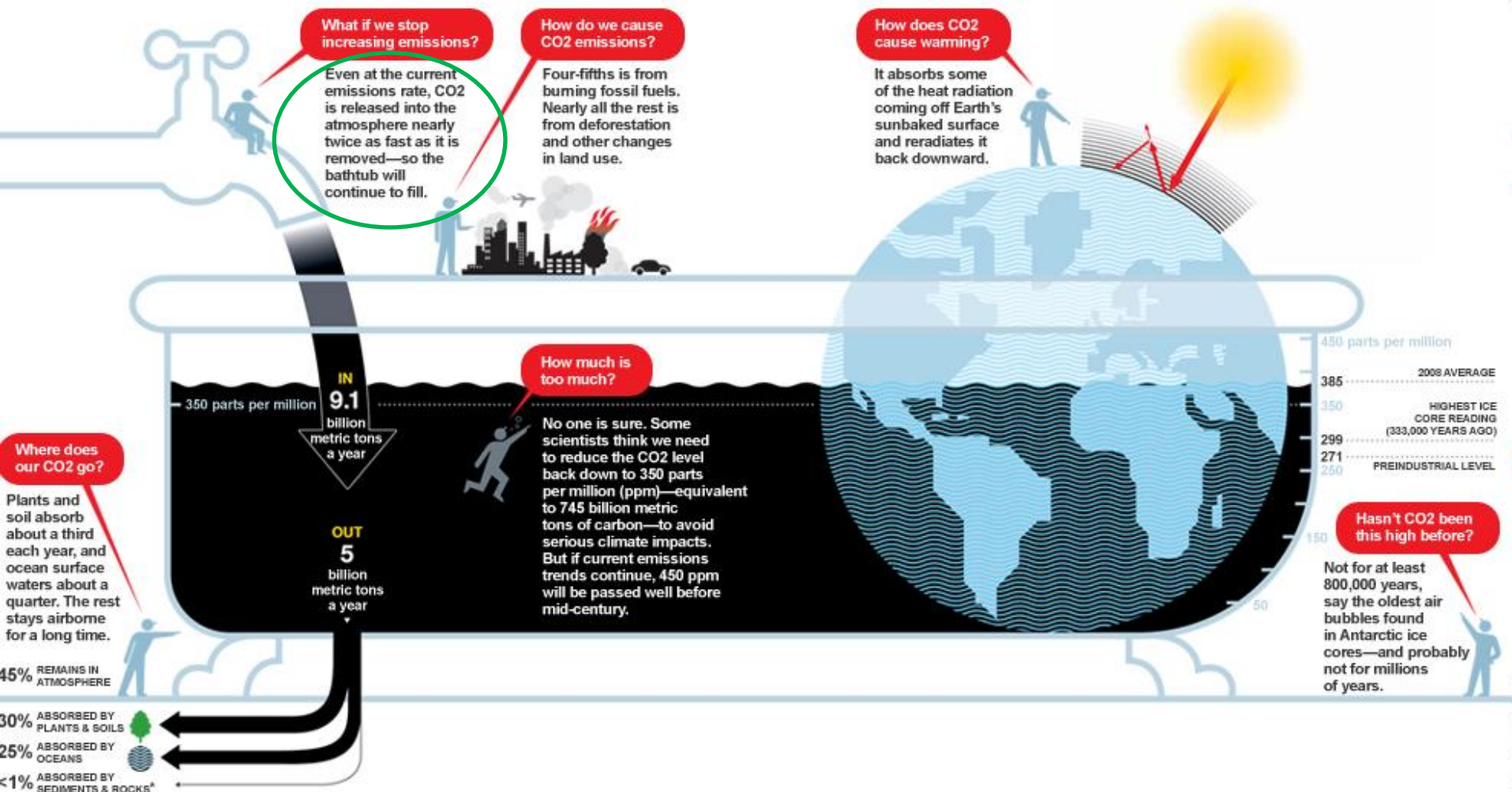
Even though our planet is ~75% water, the **largest** movement of carbon (flux) actually happens between the terrestrial ecosystem and the atmosphere (the greatest percent of that is cycled through forest systems).



## Total Annual Anthropogenic GHG Emissions by Groups of Gases 1970–2010



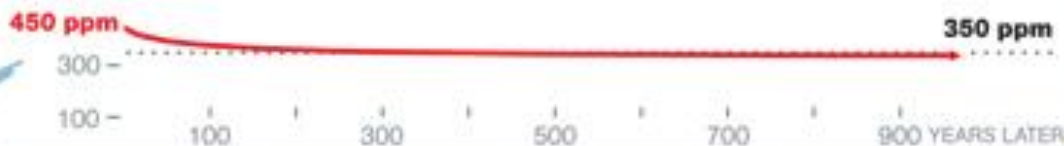
**Figure SPM.1** Total annual anthropogenic GHG emissions (GtCO<sub>2</sub>eq/yr) by groups of gases 1970–2010: CO<sub>2</sub> from fossil fuel combustion and industrial processes; CO<sub>2</sub> from Forestry and Other Land Use (FOLU); methane (CH<sub>4</sub>); nitrous oxide (N<sub>2</sub>O); fluorinated gases<sup>8</sup> covered under the Kyoto Protocol (F-gases). At the right side of the figure GHG emissions in 2010 are shown again broken down into these components with the associated uncertainties (90 % confidence interval) indicated by the error bars. Total anthropogenic GHG emissions uncertainties are derived from the individual gas estimates as described in Chapter 5 [5.2.3.6]. Global CO<sub>2</sub> emissions from fossil fuel combustion are known within 8 % uncertainty (90 % confidence interval). CO<sub>2</sub> emissions from FOLU have very large uncertainties attached in the order of ±50 %. Uncertainty for global emissions of CH<sub>4</sub>, N<sub>2</sub>O and the F-gases has been estimated as 20 %, 60 % and 20 %, respectively. 2010 was the most recent year for which emission statistics on all gases as well as assessment of uncertainties were essentially complete at the time of data cut-off for this report. Emissions are converted into CO<sub>2</sub>-equivalents based on GWP<sub>100</sub><sup>6</sup> from the IPCC Second Assessment Report. The emission data from FOLU represents land-based CO<sub>2</sub> emissions from forest fires, peat fires and peat decay that approximate to net CO<sub>2</sub> flux from the FOLU as described in chapter 11 of this report. Average annual growth rate over different periods is highlighted with the brackets. [Figure 1.3, Figure TS.1]



\* PERCENTAGES DO NOT ADD UP TO 100 BECAUSE OF ROUNDING.

What if we stop emissions completely?

It will take centuries for plants and the ocean to soak up most of the human-made CO<sub>2</sub>. It will take hundreds of millennia for the rest to be removed by rock weathering, which converts CO<sub>2</sub> to carbonate sediments and rocks.



DRAINS FROM TUB

Plants and soil absorb CO<sub>2</sub> quickly, but that reservoir fills up fast.

PLANTS  
& SOIL

Why would the level stay high for so long?

The deep ocean is bigger, but access is slow; CO<sub>2</sub>-laden surface water sinks at only two places near the Poles.

DEEP OCEAN

Carbonate sediments and rocks are far bigger and slower still; they form at sea from elements weathered off rocks on land.

SEDIMENTS & ROCKS





**“Data! Data! Data!  
I can't make bricks  
without clay”**

**Sherlock Holmes**

# Carbon dioxide concentrations correlate to glacial/interglacial periods in earth's history

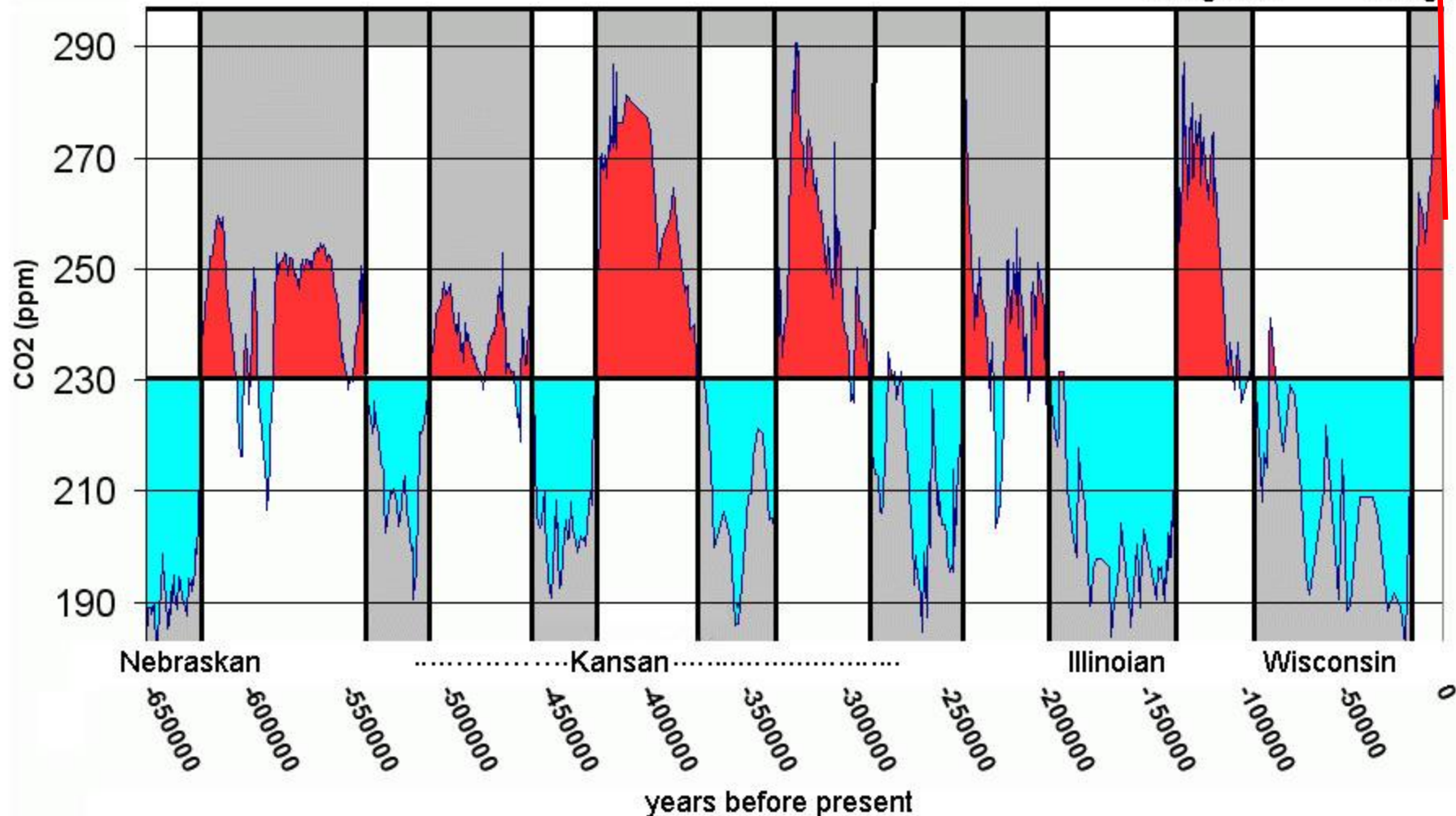
400 ppm CO<sub>2</sub>

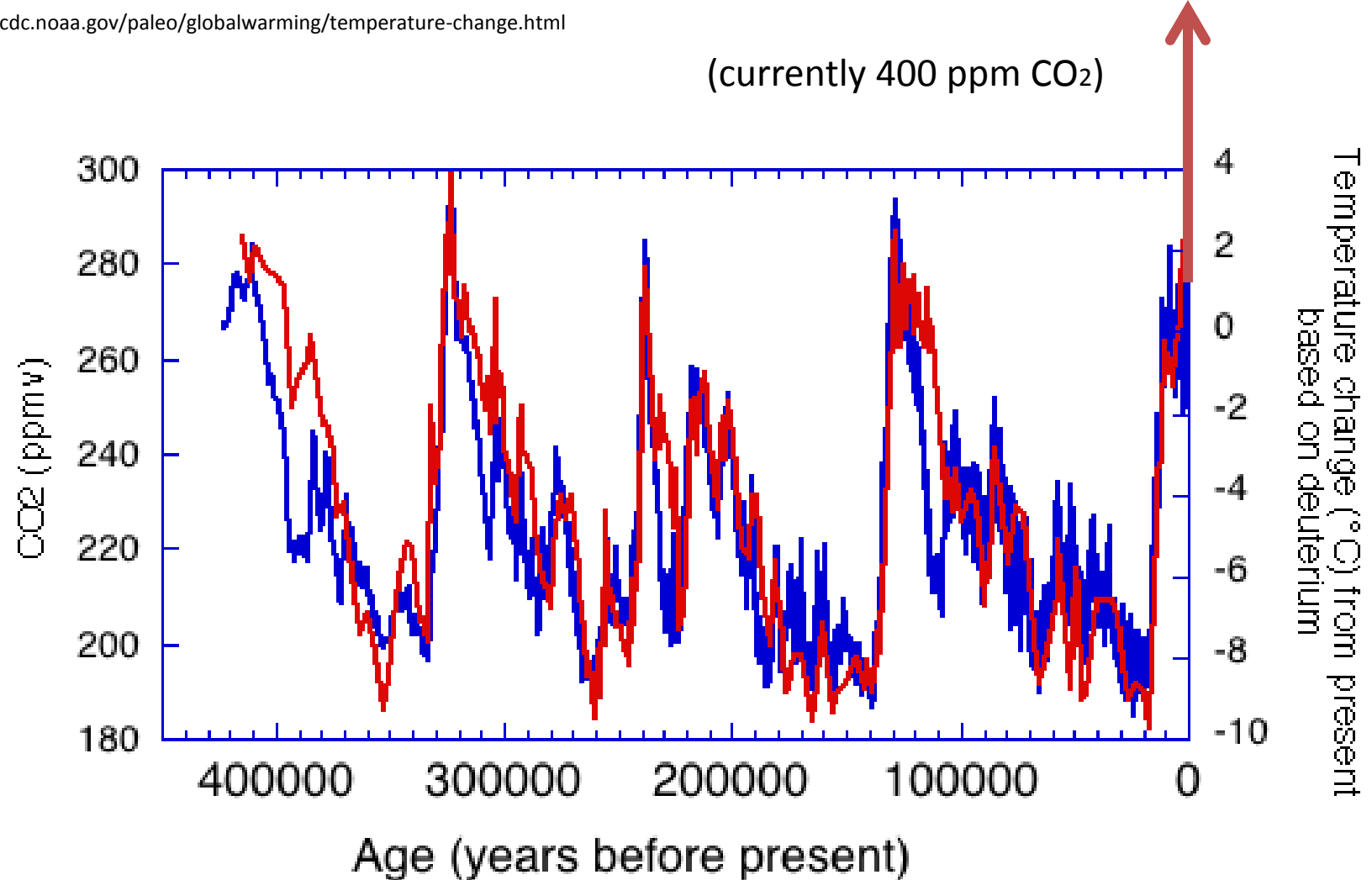
## Late Pleistocene glaciations compared with atmospheric CO<sub>2</sub> concentrations from glacial ice

(650,000 to 0 years before present)

(CO<sub>2</sub> concentrations in parts per million [ppm])

Stage 13 12 11 10 9 8 7 6 5 4 3 2 1  
Aftonian Interglacial Yarmouth Interglacial Sangamon Interglacial Holocene Interglacial





### **Carbon dioxide and temperature as measured in ice cores**

“The atmospheric concentrations of carbon dioxide, methane, and nitrous oxide have increased to levels unprecedented in at least the last 800,000 years. Carbon dioxide concentrations have increased by 40% since pre-industrial times, primarily from fossil fuel emissions and secondarily from net land use change emissions. The ocean has absorbed about 30% of the emitted anthropogenic carbon dioxide, causing ocean acidification.” IPCC AR5

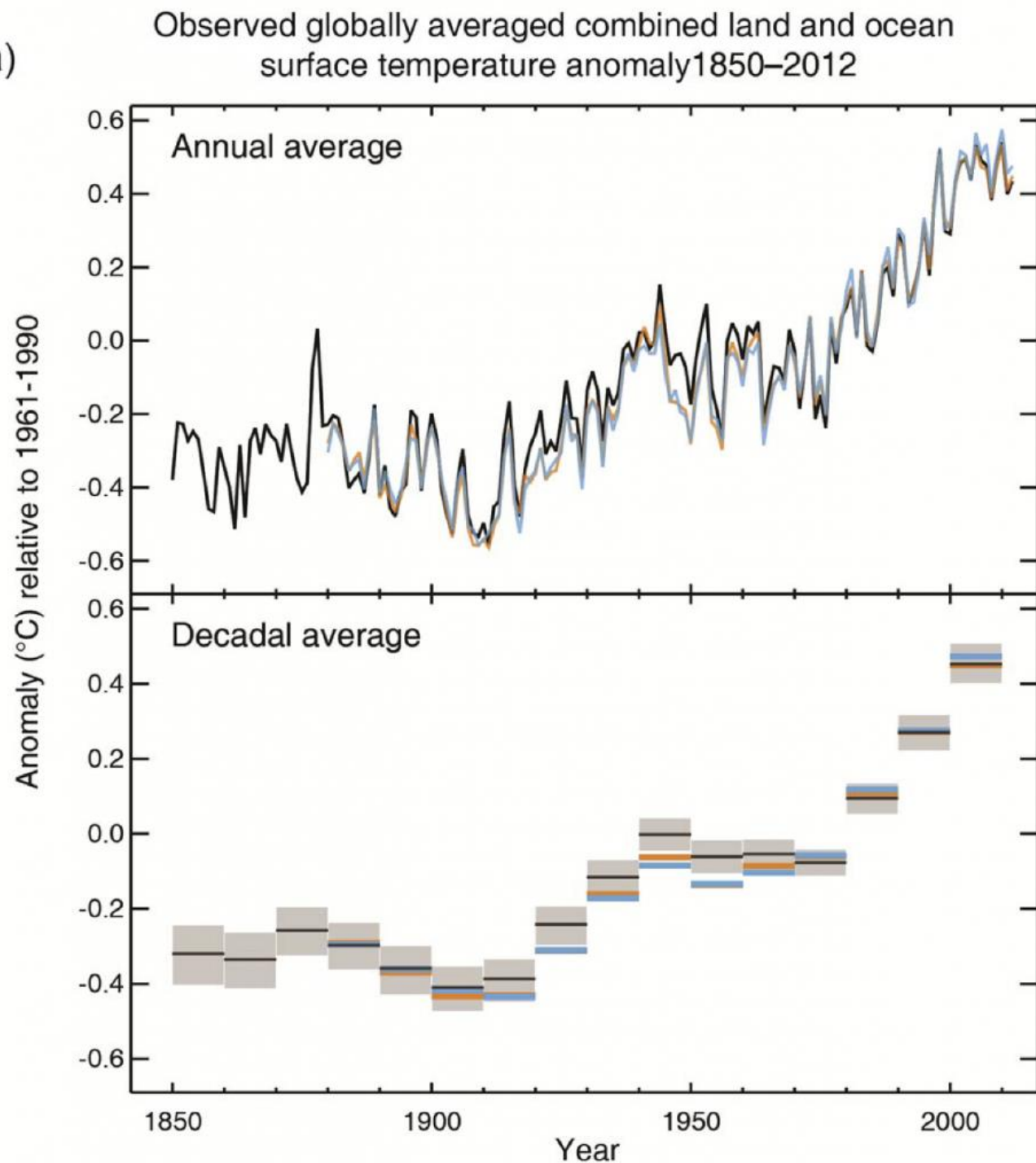
# Field notes from a catastrophe

(title stolen from book by E. Kolbert)

## The warming is unequivocal

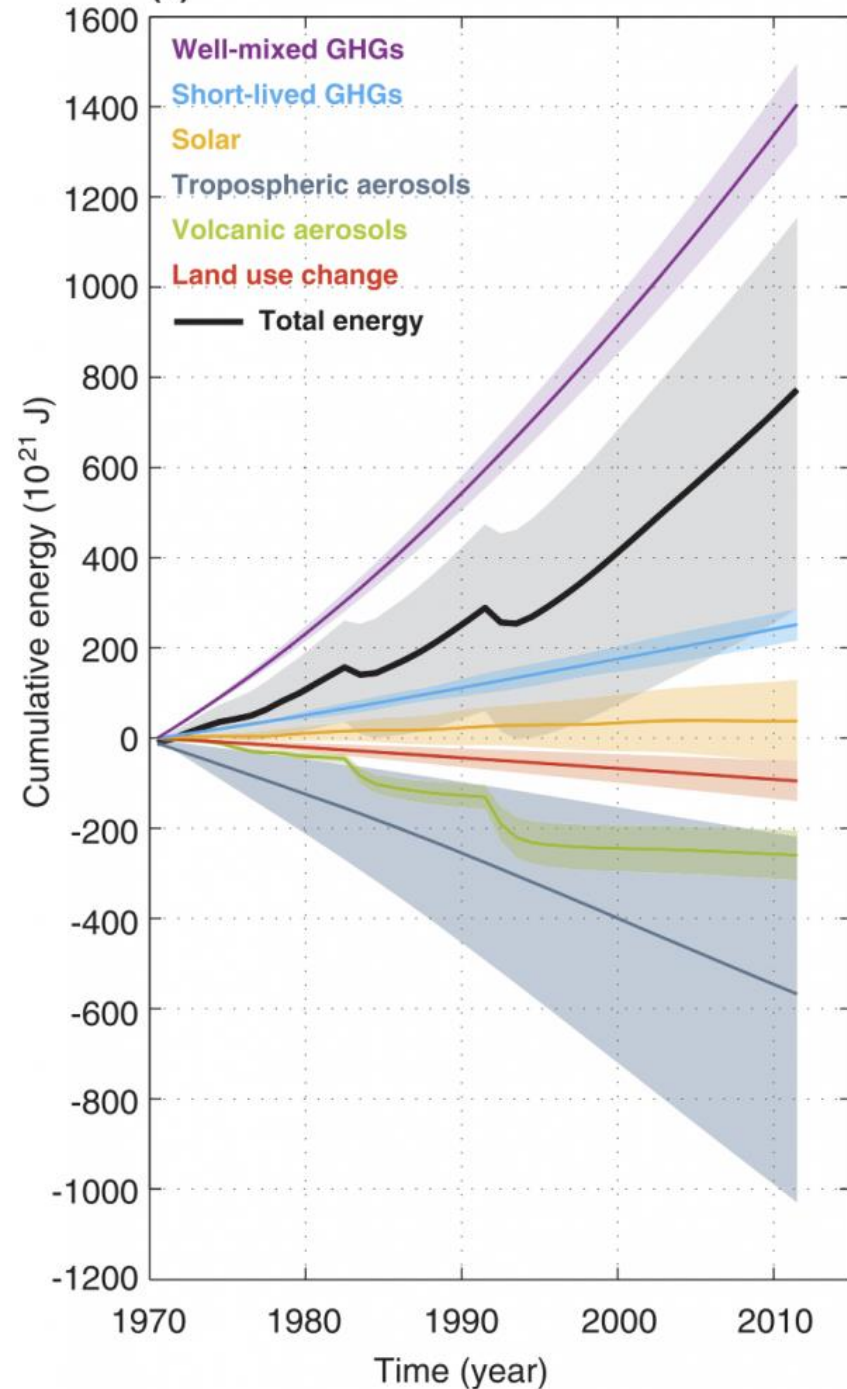
*“Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia.”*

IPCC AR5





(a)

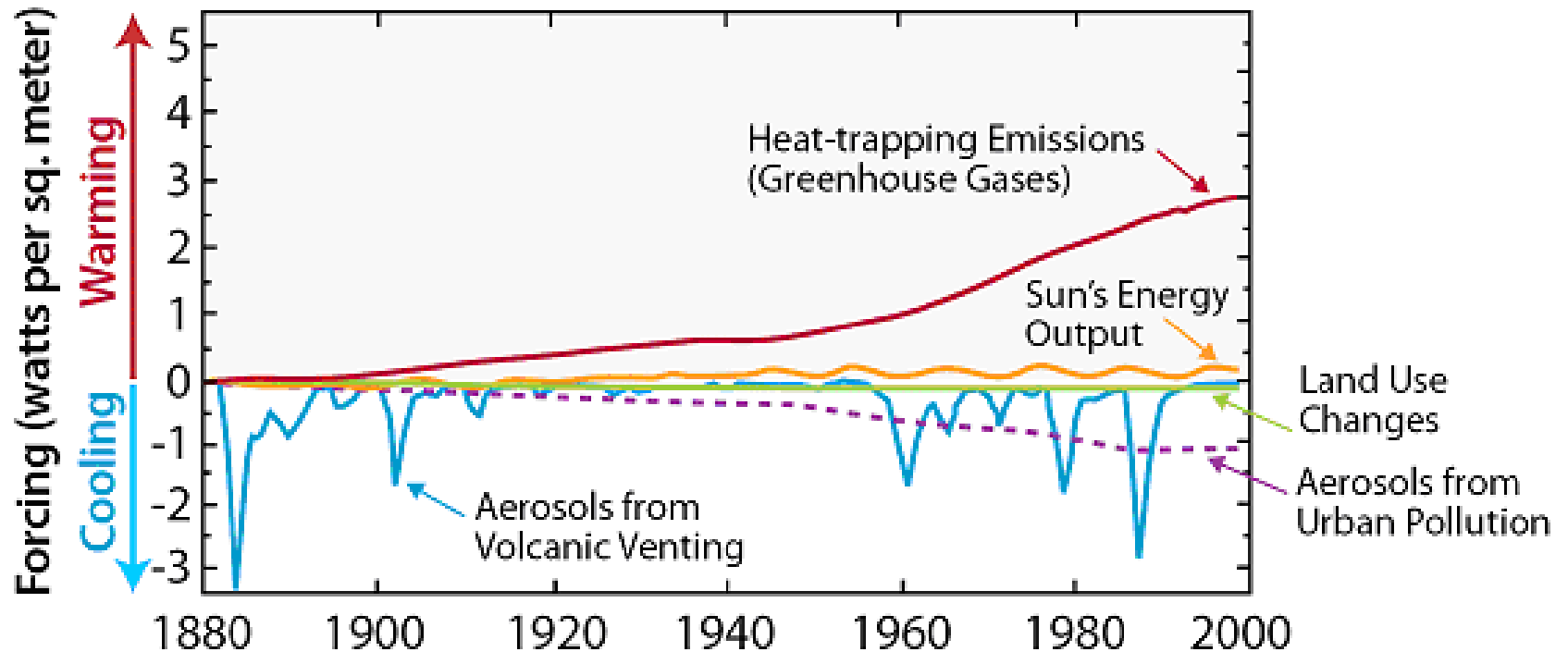


**Humans caused the majority of it**

*“It is extremely likely that human influence has been the dominant cause of the observed warming since the mid-20th century”.*

IPCC AR5

# Global Climate Drivers



## Relative contribution of elements of radiative forcing

**MANY different scenarios of our future were modeled, IPCC chose four representative possibilities:**

RCP8.5 represents 'business as usual' – strong economic development for the rest of this century, driven primarily by dependence on fossil fuels.

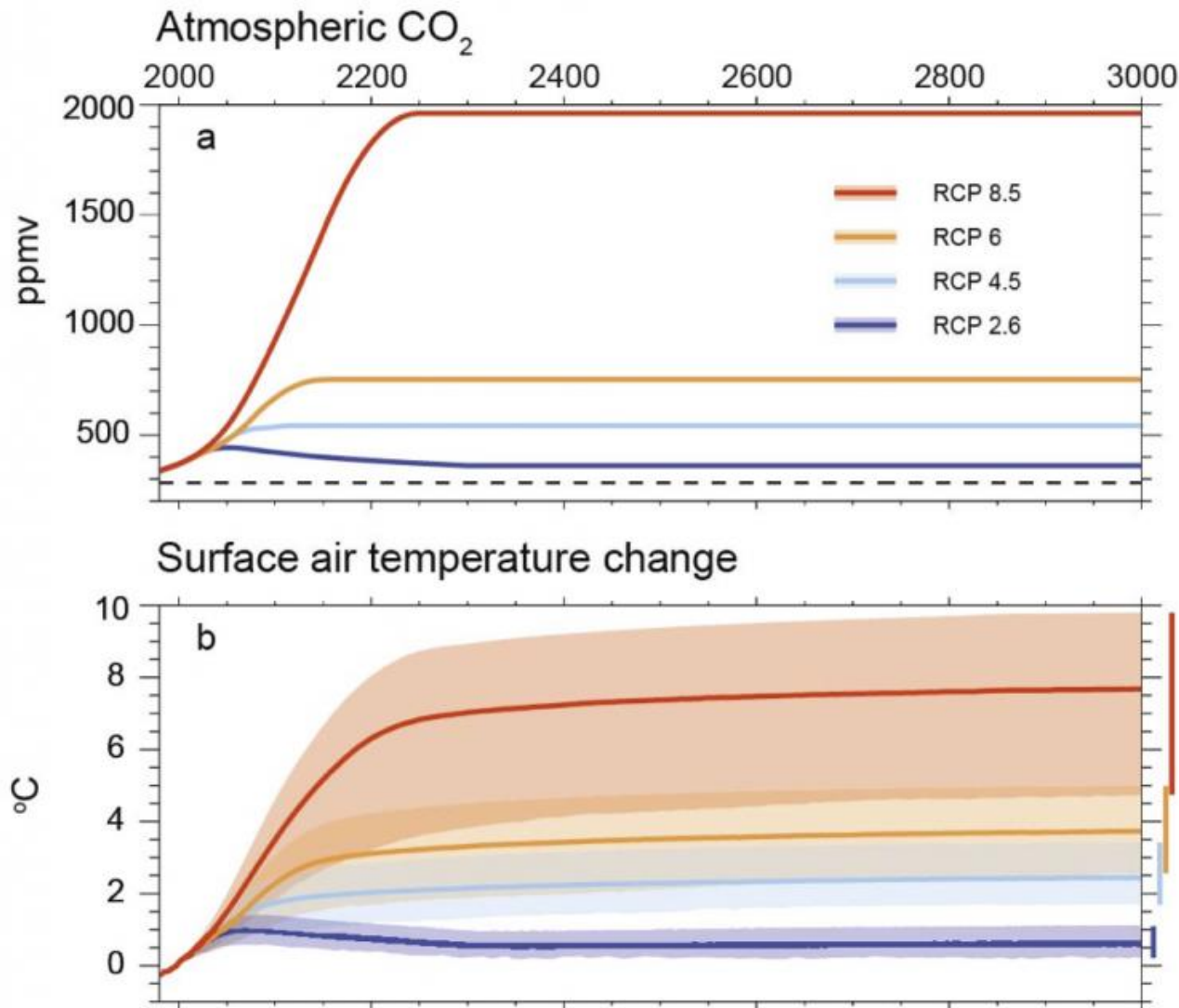
RCP6 represents a world with no global coordinated climate policy, but where lots of localized clean energy initiatives do manage to stabilize emissions by the latter half of the century.

RCP4.5 represents a world that implements strong limits on fossil fuel emissions, such that greenhouse gas emissions peak by mid-century and then start to fall.

RCP2.6 is a world in which emissions peak in the next few years, and then fall dramatically, so that the world becomes carbon neutral by about mid-century.



## The warming is largely irreversible

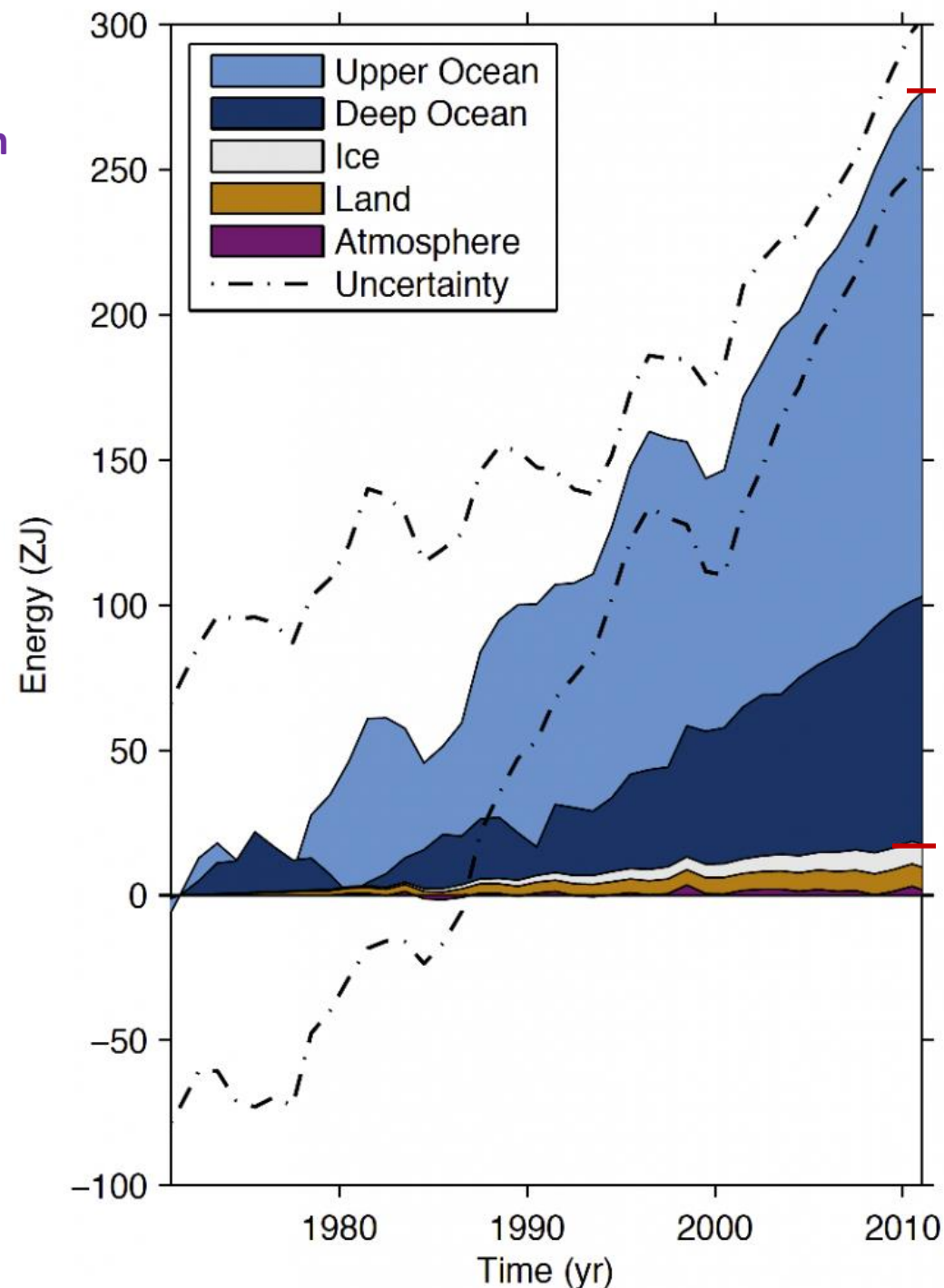


*“A large fraction of anthropogenic climate change resulting from CO<sub>2</sub> emissions is irreversible on a multi-century to millennial time scale, except in the case of a large net removal of CO<sub>2</sub> from the atmosphere over a sustained period. Surface temperatures will remain approximately constant at elevated levels for many centuries after a complete cessation of net anthropogenic CO<sub>2</sub> emissions.”*

## Much of this warming (energy) is stored in the ocean water

The oceans have a huge thermal mass compared to the atmosphere and land surface. They act as the planet's heat storage and transportation system, as the ocean currents redistribute the heat. This is important because if we look at the global surface temperature as an indication of warming, we're only getting some of the picture. The oceans act as a huge storage heater, and will continue to warm up the lower atmosphere (no matter what changes we make to the atmosphere in the future).

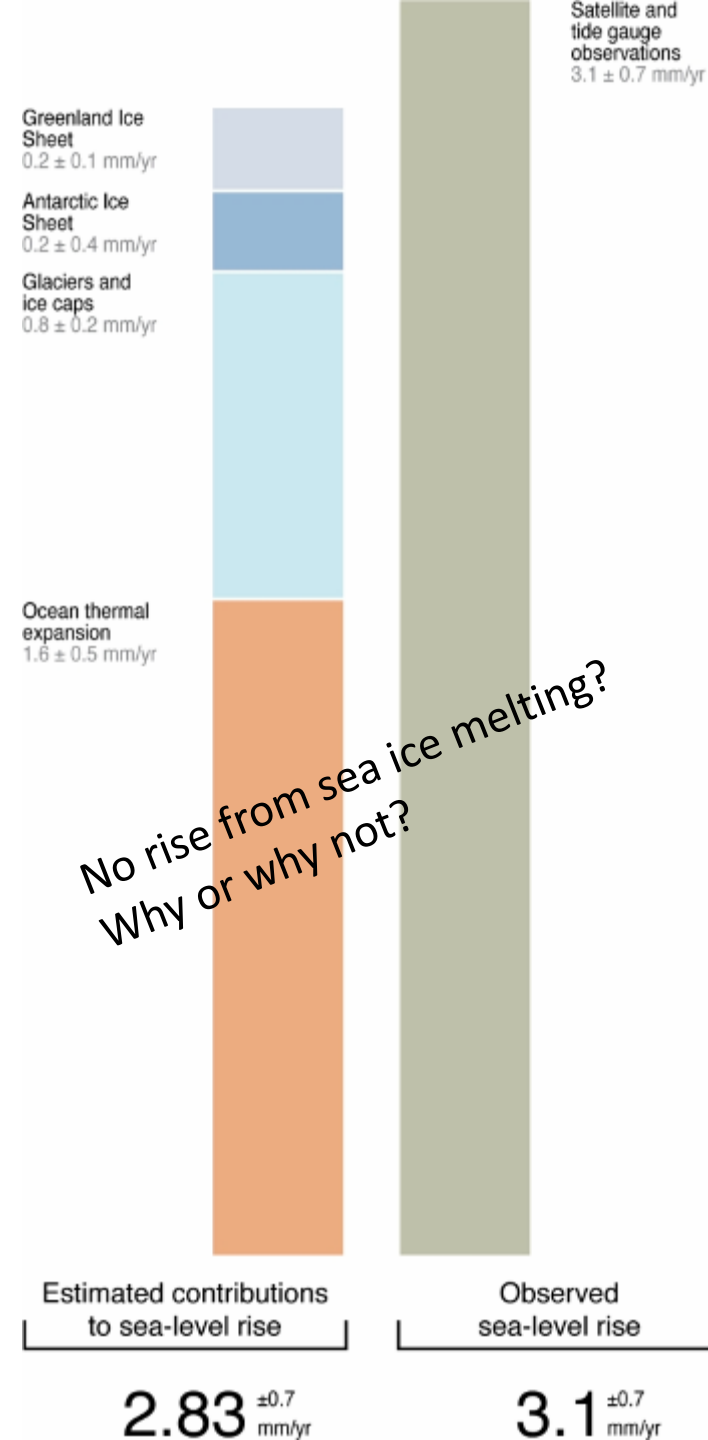
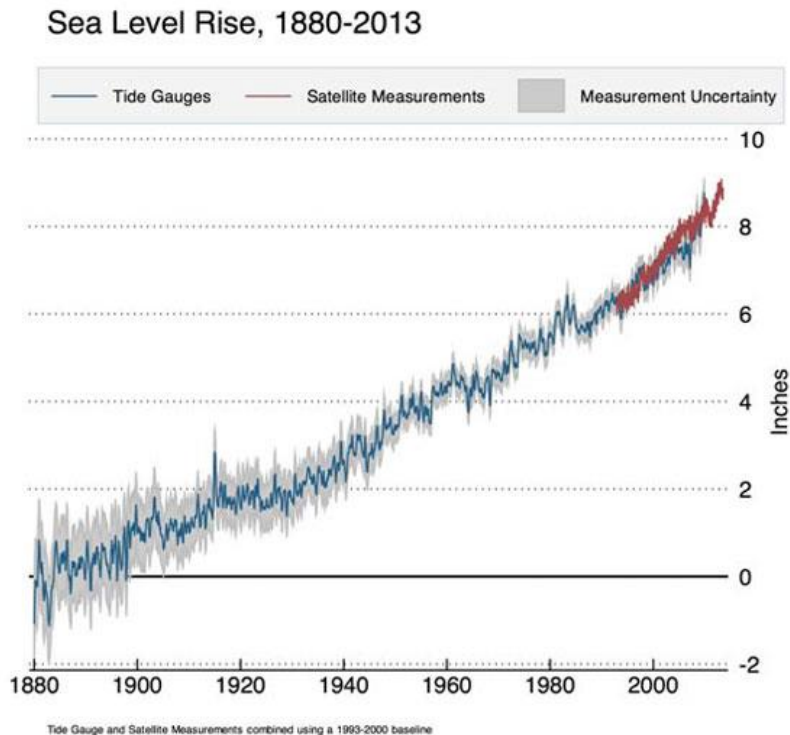
**According to this figure, what percent of warming is stored by the oceans?**  
**~85%**



This stored heat/energy is also impacting average global sea level

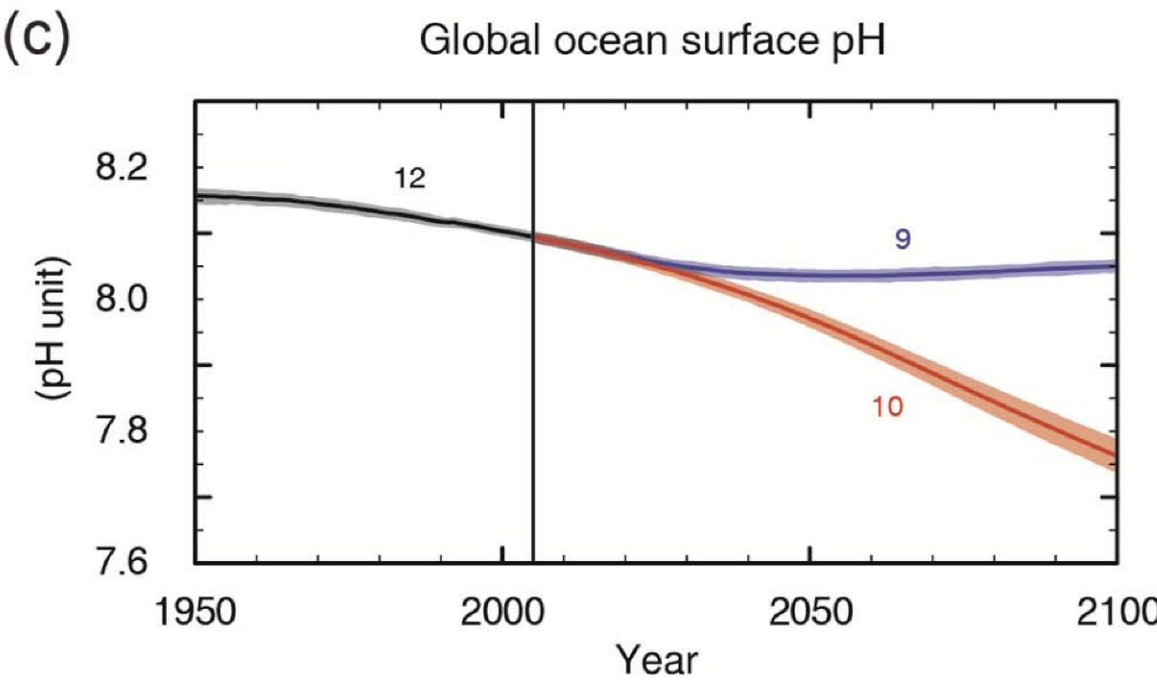
Which of the following has the largest impact on sea level rise?

- a. Melting of glaciers
- b. Melting of ice sheets
- b. Melting of sea ice
- c. Thermal expansion of ocean



**Current rates of ocean acidification are unprecedented.**

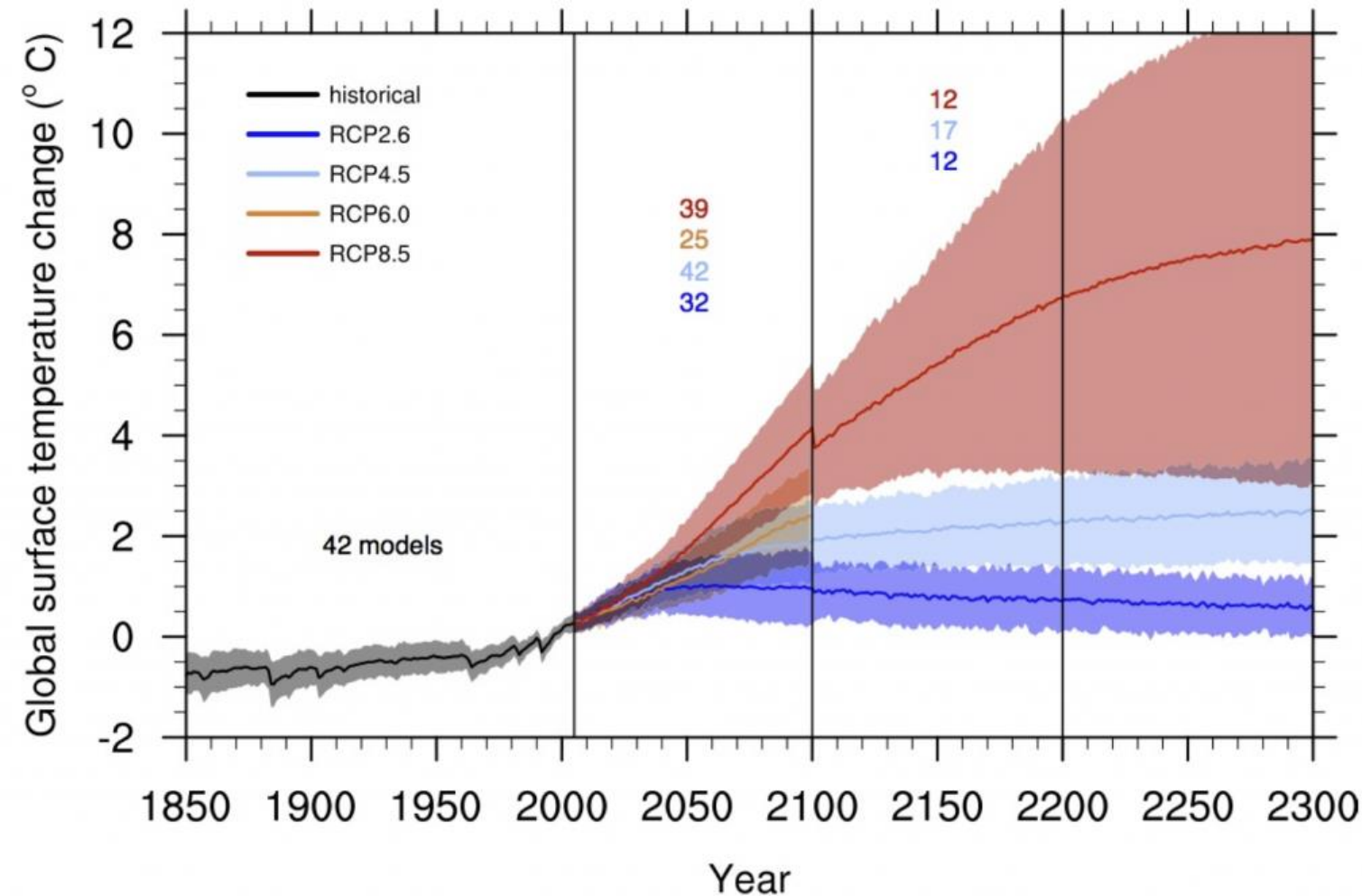
*“The pH of seawater has decreased by 0.1 since the beginning of the industrial era, corresponding to a 26% increase in hydrogen ion concentration. ... It is virtually certain that the increased storage of carbon by the ocean will increase acidification in the future, continuing the observed trends of the past decades. ... Estimates of future atmospheric and oceanic carbon dioxide concentrations indicate that, **by the end of this century, the average surface ocean pH could be lower than it has been for more than 50 million years**”.*



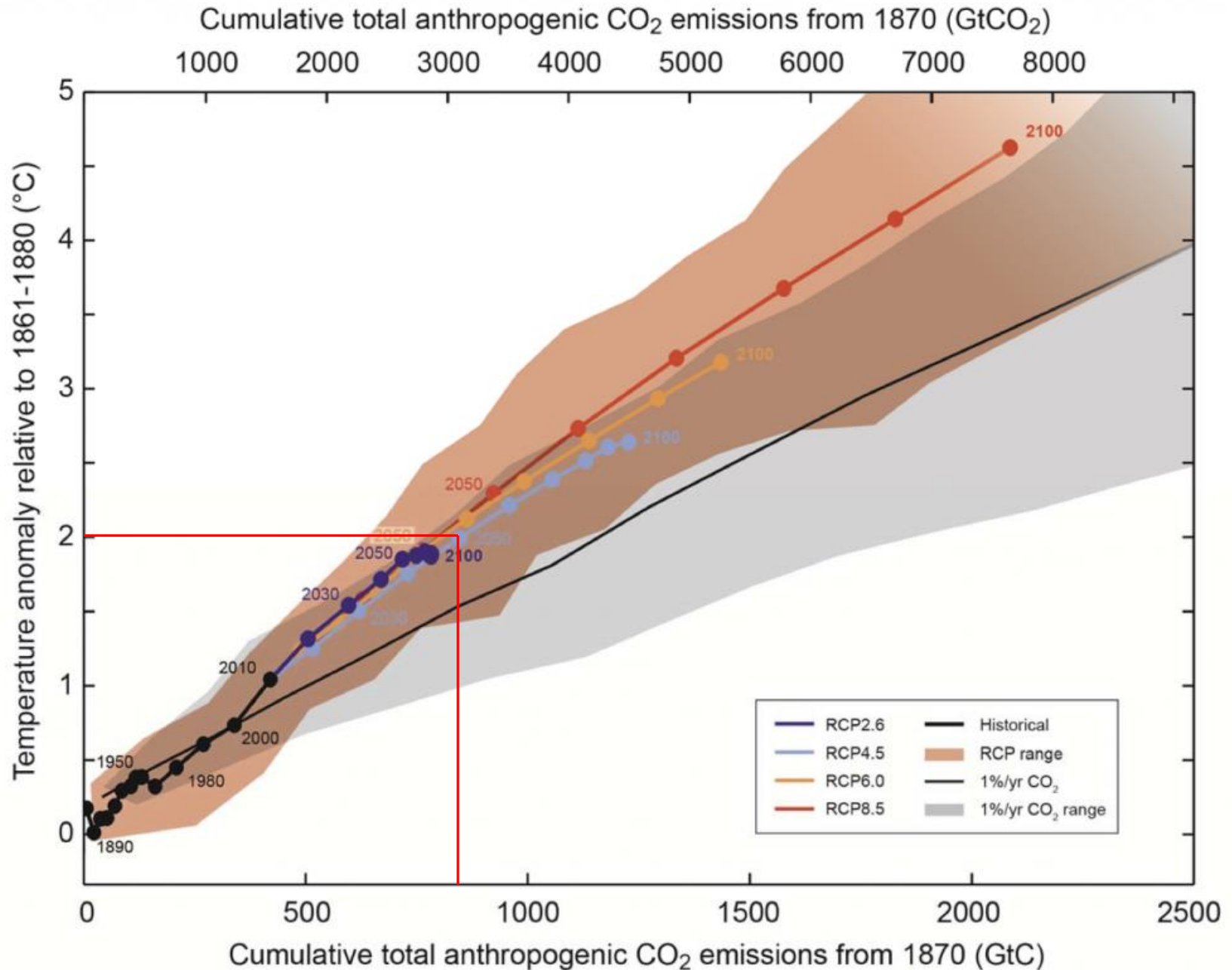
"We balance probabilities and choose the most likely. It is the scientific use of the imagination"

A. Conan Doyle. *The Hound of the Baskervilles* (1902)

The models are clear, 'business as usual' isn't pretty



To stay below 2°C of warming, most fossil fuels must stay buried in the ground.





To give us a 33% chance of staying below 2°C of warming over pre-industrial levels, we cannot ever emit more than **880** gigatonnes of Carbon.

To give us a 50% chance, we cannot ever emit more than **840** gigatonnes of Carbon.

To give us a 66% chance, we cannot ever emit more than **800** gigatonnes of Carbon.

### HOW MUCH HAVE WE EMITTED SO FAR?

Since the beginning of industrialization, we have already emitted a little more than 500 GT. So our remaining budget is somewhere between 300 and 400 GT. Existing known fossil fuel reserves are enough to release at least 1000 GT!

New discoveries and unconventional sources will likely more than double this. That leads to one inescapable conclusion:

***To stay below the agreed upon 2C warming target, most of the remaining fossil fuel reserves must stay buried in the ground.***